Table of Contents

Jump into STEM: A Case Study in Student Research

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Jump into STEM is a Department of Energy Challenge for undergraduate and graduate college students. The challenge focuses on innovate technologies for energy resources for the future. Similar to the Solar Decathlon, there are opportunities for construction students to participate in a national level competition while providing opportunities for a variety of research pathways. The Challenge encourages a diverse team, allowing students to find research funding through existing programs at the university through non-traditional sources like the Louis Stokes Alliance for Minority Participation program. Applicable coursework and pedagogy are discussed. Students applied a variety of construction skills during the project. Examples of research frameworks and an overview of how the project was completed are provided. The case study is a success story in interdisciplinary research across multiple education levels where the construction program does not have a graduate student program.

Key words: Undergraduate Research Funding, Jump into STEM, Louis Stokes Alliance for Minority Participation, Interdisciplinary Construction Student Research

Introduction and Literature Review

Students from within the Oklahoma State University Construction Engineering Technology undergraduate and Civil Engineering graduate programs were recruited to participate in the Department of Energy (DOE) (DOE 2020) Jump into STEM Challenge (2022). The challenge is not funded during the student research phase. However, the winning teams receive a 10-week paid summer internship at the National Renewable Energy Laboratory, the Oak Ridge National Laboratory, or the Pacific Northwest National Laboratory (Jump into STEM 2022).

As this project is unfunded during the research phase, some of the students were performing this research in conjunction with non-traditional funding sources. One such source is the Oklahoma Louis Stokes Alliance for Minority Participation (LSAMP) Program which services which is a consortium of universities within the state and supports minority students interested in research. The LSAMP program is funded through the NSF but does not require a specific STEM research area for the students (NSF 2022), so interdisciplinary or multi-disciplinary research can be supported. Unfunded research projects and competitions are frequently seen in undergraduate education for students who are motivated for extra-curricular work. The CET program is a regular participant in the Associated Schools of Construction regional estimating competition. Similar programs are found nationwide including the American Society of Civil Engineers Concrete Canoe competition or the Solar

Decathlon (Schuster et al. 2006). Group participation projects align with an active learning pedagogy (Pantoya et al. 2013).

The CET degree at Oklahoma State University include requirements for engineering economics and technical writing. Engineering economics included benefit- cost analysis, as do other courses in the degree program. However, for a technologist or a graduate of an engineering technology program, it more likely to be focused on broad based problem solving, versus problem definition and solutions (Floyd 2019). The English Department, and its technical writing faculty, understand the need for identifying a problem and presenting research, which is supported by research (Hepworth 2009). Undergraduates seek literature as part of research projects, frequently through library services. Providing seminars about library services has been found to increase student knowledge of materials outside of the traditional books and periodicals (Hallman and Chang 2020). Information Literacy (IL) describes the ability to find, understand and communicate information. While IL has been focused on the library in the past with online resources, IL now includes the ability to find, understand and communicate information found through the computer (Pinto et al. 2022). However, students may still find a literature review difficult due to the amount and availability of information and sources (Pinto et al. 2022).

Problem-based learning (PBL), an active learning pedagogy, requires the student to create a problem statement which can be difficult for a student (Schaub et al. 1999 and Pantoya et al. 2013). The fishbone diagram can be utilized to help students relate cause and effect to develop the cause of an unsolved problem (Priyadi and Suyanto 2019). Construction students frequently favor an active learning approach over traditional lectures (Abraham 2020) or an online learning environment (Kirkmann and Mosier 2022). An active learning approach aligns with the use of internships in Construction Management majors (Siddiqi and Ozcan 2004 and Moore and Plugge 2008). Internships can provide summer pay and are also considered to be a stepping-stone into long-term construction employment and higher starting salaries (Siddiqi and Ozcan 2004).

This case study includes discussion of three issues which were overcome. Unfunded students who do not need a research project for graduation may lack motivation to complete difficult projects (Schuster and Birdsong 2006). An additional concern with undergraduate students, is the need for longevity in a project (Schuster and Birdsong 2006). A third, unexpected issue was having students self-motivate for research during an ever-changing response to Covid (Pinto et al. 2022). The case study also describes the work product of the research teams and the final result.

Background

The "Jump into STEM" challenge is a student-centered research program supported by the Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (EERE) with annual topics under the Buildings Energy Efficiency Frontiers & Innovation Technologies (BENEFIT) – 2020 funding opportunity. In 2020, these topics were 1) Building Technology Research, Development and Field Validation and 2) Advanced Building Construction. Under Topic 2, Advanced Building Construction, subtopics were Advanced Building Construction. Under this subtopic was "Advanced Robotics, Tools, and Methods for Retrofits," which was chosen by the student team as an area of interest. The DOE additionally required, as written (2020):

> *All applications to Advanced Robotics, Tools, and Methods for Retrofits should define the "next best alternative" technology or practice (e.g. the baseline or state of the art) and describe how their solution significantly improves over this baseline in terms of cost reductions, invasiveness, installation time, and installation safety. Applications must address and quantify the following:*
> *• Energy savings, affordability, demand flexibility, and occupant comfort*

- *Description of the manner and extent by which their approach advances the state of the art*
- *Relevant metrics (links provided)*

The Construction Engineering Technology (CET) program at Oklahoma State University has been an undergraduate program only since its inception. The program began a partnership with the School of Civil Engineering in 2015 to support of graduate students in the construction research area. Previously the CET program only had access to undergraduate students for research. CET faculty relied on the LSAMP (NSF 2022) for minority students seeking financial support as research scholars. With the new partnership, graduate students seeking research opportunities in construction have been funded via teaching or research assistantships, as is traditional for many universities.

When considering that the CET faculty were teaching focused until 2014, there is not an established research program. New faculty are expected to create their own research program where there was no existing research funding. Likewise, there is not a graduate degree offered in CET which means that undergraduate students are much more available. These challenges to create a research program are not insurmountable but have been identified at other universities (Schuster and Birdsong 2006).

The Challenge

The challenge identified by the DOE, Advanced Building Construction Methods required,

> "*…an innovative solution incorporating substantial changes in building materials or construction methods, leading to benefits such as increased productivity and worker safety though reduced construction time, reduced cost and was, improvements to occupant comfort and health, and reduced energy use."* (Jump into STEM 2020)

The DOE "Jump into STEM" (JUMP) challenge is open to teams of 2-4 students. Although all of the team must be current students, there is not a limitation to their major or degree level. JUMP does take into factor the diversity of the team as well as the challenge submission (Jump into STEM 2022). Our student-researchers represented a variety of ethnicities, genders, nationalities, and majors, both undergraduate and graduate students. Two teams of four students worked on the Jump into STEM challenge, one team in 2020-21 and another in 2021-22. The 2020-21 team was made up of two undergraduate CET students, an undergraduate Mechanical Engineering student and one civil engineering doctoral student. They were funded by LSAMP stipends and Research or Teaching Assistantship salary respectively. The 2021-22 team was made up of two undergraduate CET students, a civil engineering master's student and civil engineering doctoral student. The undergraduate students on this team were not funded through any mechanism, while the graduate students received Research or Teaching Assistantship salary. An overview of the demographics is provided in Table 1. *Note the doctoral student participated in both years.

Table 1

Demographics of Student Researchers

Major	Degree	Ethnicity	Gender	Funded
CET - 4	Baccalaureate - 5	Asian - 1	Female - 1	Yes – 5
Civil Eng. - 2	Master -1	Hispanic - 3	Male - 6	No - 2
Mech. Eng. -1	Doctoral -1*	White - 3		

A proposed research methodology flow was created which consisting of four phases: Phase 1: Dimension Development, Phase 2: Multi-Criteria Decision Making, Phase 3: Life Cycle Cost Analysis, and Phase 4: Benefit-Cost Analysis (BCA) (see figure 1). Phase 1 Dimension Development included identifying Key Performance Index (KPI) dimensions (including economic), construction, technology, social/environmental, energy, and mechanical criteria as identified in the fishbone diagram. Phase 2 Multi-Criteria Decision Making (MCDM) included Choosing by Advantages (CBA), which was conducted to determine the best option by comparing alternatives. CBA weights options based on importance and can support collaborative group-based decision making (Kpamma et al. 2016). Phase 3 Life Cycle Cost Analysis (LCCA) was conducted for financial analysis. Phase 4 Incremental Modeling, a BCA technique, was performed to evaluate and to provide a graphical representation of the more beneficial options among the robotics selected for review.

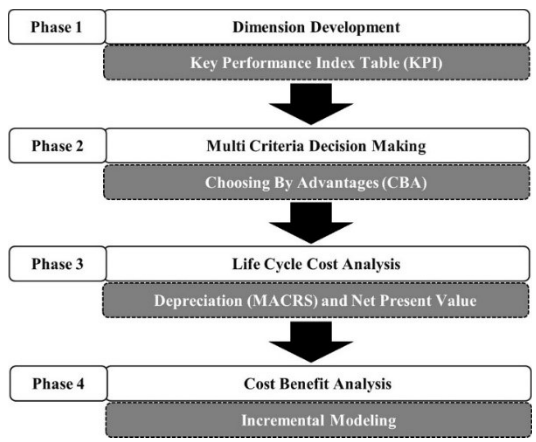

Figure 1. Proposed Research Methodology

In 2020-21, our team responded to the challenge with a submission titled "Sustainability Performance Analysis in Robotics of Construction." During initial meetings to define the problem, the faculty and students created a fishbone diagram (see figure 2). During this time, students identified their own areas of interest for the literature review and a cause-and-effect relationship within the research project (Clary and Wandersee 2010).

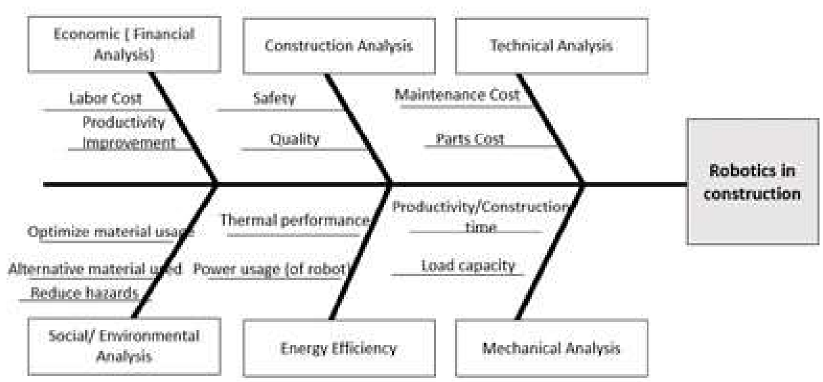

Figure 2. Student Research Fishbone Diagram

The team proposed a comparison of conventional construction methods with the use of robotics in the construction industry, and to evaluate construction impacts, social impacts, environmental impacts, energy impacts utilizing a life cycle cost analysis based on the leading robotics in the construction industry. Using the relationships identified in the fishbone, the students developed the following research statement; "as artificial intelligence and advanced robotics have pushed to the forefront of the world's attention; many companies have made great strides in applying more robotics in the construction industry." Based on their initial literature review, the student team selected three emerging technologies from available construction robotics: rebar tying robot (TyBot), a GPS skid steer (GPS3), and a 3D concrete printer (3DCP) to evaluate the sustainability performance in robotics in construction based on a variety of robotic types and categories.

One of the student research findings from the BCA was although TyBot had the highest costs, better benefits were predicted for the sustainability performance. Based on the MCDM, productivity was identified as the most important Key Performance Index (KPI). Based on our analysis, TyBot was rated better not only in productivity, but also in the durability and technical dimension, while having the lowest environmental impact. Meanwhile, the comparison between the GPS3 and 3DCP indicated the GPS3 was more beneficial based on the BCA. The selection of the construction robots was determined using an innovative "sustainability performance analysis" approach, utilizing construction schedules and budgets to minimize project cost while satisfying long-term performance goals of the project. Additionally, the proposed sustainability performance analysis was not limited to the robotics in construction. The "sustainability performance analysis" approach can be applied to any emerging technology for evaluation. The emerging technologies, which included robotics, will not only increase production, but also increase efficiency, quality, and safety, reduce waste, aid in quick-response scenarios, and create a platform for even greater future growth of robotics and innovation in the construction industry.

In 2021-22, our team responded to the challenge with a submission titled "R3ER (Resilient, Equitable, Environmental, Energy efficiency, Rapid) Shelter Design." One student returned to the research team with requisite knowledge and interest in the project. The second research team expanded on the knowledge of emerging technology robotics from the previous year. The research design methodology is presented as a schematic diagram with emphases in Construction, Design, Energy and Case Study (see figure 3).

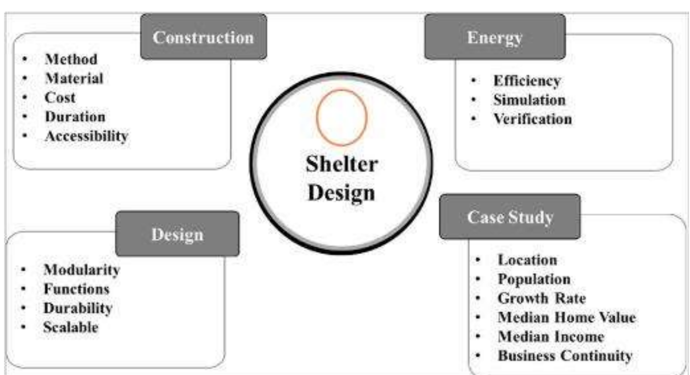

Figure 3. Schematic diagram for Shelter Design

From these overarching emphases, the team extended the research and R3ER Shelter Design to include 1) a 3D printing based construction method, 2) multiple design functions of the shelter design, 3) energy efficiency, and 4) an economic analysis to indicate market readiness, which included a case study. The case study was a holistic real-world scenario for the project to be modeled around and ensure implementation of the four emphases. The R3ER Shelter was designed not only as a disaster resistant shelter but also for multi-purpose uses including a hotel, office, or hospital pre- or post-disaster. Additionally, R3ER Shelter design team analyzed energy efficiency using Energy Plus. The Energy Use Intensity (EUI) is compared with the benchmark EUI approved by ASHRAE Standards Committee. The R3ER Shelter energy consumption is established below the targeted energy, which suggests the energy consumption of the model is below any permissible limit. Accordingly, the proposed shelter design optimized all aspects of building construction, including the structure, enclosure, and energy systems. The R3ER Shelter will provide any future stakeholders such as emergency planning commissions, third party organizations, and construction managers/engineers a resource to maximize both monetary and non-monetary benefits of using the R3ER Shelter. Communities would not only be less exposed to disaster damage or less vulnerable to disaster impacts, but also ensured of the maximum response based on limited resources to serve the largest number of persons affected by a disaster.

Methodology

In 2020-21, the team had different semester schedules and were not on campus due to Covid-19 precautions. The team utilized video conferencing 1) to meet two times per week, which encouraged members to collaborate as a team under the Covid-19 precautions, and 2) to communicate and check each task in detail, while supporting all members in performance of their tasks. The related coursework, i.e. Technical Writing, Engineering Economics, and internship experiences at Oklahoma State University. The collaboration provided a background for comprehensive understanding of the research methods, which included BCA, MCDM and CBA techniques. This diverse team, with their wide range of knowledge, developed the innovative methodology to evaluate the novel sustainability performance analysis" in Robotics of Construction utilizing construction schedules and budgets to minimize project cost while satisfying long-term performance goals of the project.

In 2021-22, there was a change in team membership and Covid-19 precautions changed. The only returning member, a doctoral student, acted as the overall project lead, managing data input, scheduling meetings, designing the shelter structure, designing the research structure, and developing the structure of the report. The graduate students were responsible for the background and methodology, providing a list of major design elements, analysis of the current state of 3D printing, and the energy efficiency analysis. The energy simulation was conducted to determine energy consumption of the R3ER shelter with the help of software Sketchup and Openstudio. A few considerations are set for the simulation such as Large Hotel building type, ANSI/ASHRAE/IES standard 90.1-2010 template, and ASHARE 169-2006-3A climate zone. They performed a whole building energy simulation for the structure of the R3ER Shelter for heating, cooling, ventilation, lighting use in the shelter. Undergraduate student responsibilities included assist in literature review, gathering 3D printer information, shelter designs, and existing statistics to aid the case study. Since most of the team members have a construction background, the case study compliments their existing knowledge while using problem solving techniques in all feasible aspects: construction method, shelter design, energy efficiency, economic analysis, and funding model.

Results

Our team utilized video conferencing 1) to meet twice weekly, to encourage collaboration as a team, 2) to facilitate communication, and 3) check each task in detail, which creates an active learning mode. By explaining results, students are completing a PBL process of writing a problems statement, performing a solution and illustrating mastery of the problem. The schedule and agenda for 2021-22 team meetings are shown in Table 2. Weekly meetings were scheduled with a second optional for questions.

Table 2

Meeting schedule and agenda

Week	Meeting agenda
1	Team member greeting, Positioning
2	Idea development meeting
3	Framework meeting
4	Grad. Student1: Leading the team and idea development Student1 & Student 2: Literature review Grad. Student 2: Studying Energy Efficiency simulation
5	Grad. Student1: Leading the team and idea development Student1 & Student 2: Creating tables based on literature review Grad. Student 2: Finding simulation program for energy efficiency
6	Grad. Student1: Leading the team and idea development Student1: Existing buildings to resist to natural disasters Student2: Current Shelters in the US Grad. Student 2: Studying Energy Efficiency simulation
7	Grad. Student1: Leading the team and conducting shelter design Student1 & Student 2: Create Presentations on options Grad. Student 2: Conducting Open studio for the Energy Efficiency
8	Grad. Student1: Leading the team and creating case study Student 1: Searching for feasible locations for the case study Student2: Searching statistical results for Case Study Location Grad. Student2: Conducting Open studio for the Energy Efficiency
9	Grad. Student1: Creating Table of Contents for the technical report Student1: Presentation for the feasible locations of the case study Student2: Presentation for the statistical results for Case Study Location Grad. Student2: Result presentation for the Energy Efficiency
10	Grad. Student1: Case study presentation and correct the case study Student1 and Student2: Writing literature review Grad. Student2: Writing Energy Efficiency for the case study All: Writing the submission and appendix All: Submission

Based on the students major and career aspirations, only the graduate students submitted applications for internships at the Oak Ridge National Laboratory. The undergraduate students were all seniors and expected to graduate and accept full time employment. None of the undergraduate CET students expressed an interest in a research internship or moving into a research or academic role. The

Mechanical Engineering student had a research interest and continued into a graduate program in Civil Engineering (See table 3).

Table 3

The current status for Jump Into STEM students

Student Major	Status
CIVE, Ph.D. Student	Internship at Oak Ridge National Laboratory
CIVE, Master Student 2021-22	Internship at Oak Ridge National Laboratory
MAE Senior 2020-21 & CIVE Master Student 2021-22	Full Time Employment
CET, Senior 2020-21	Full Time Employment
CET, Senior 2020-21	Full Time Employment
CET, Senior 2021-22	Full Time Employment
CET, Senior 2021-22	Full Time Employment

Conclusions

This was the first time the Oklahoma State University (OSU) CET program competed in the DOE Jump into STEM challenge. The CET program engages graduate students from the School of Civil Engineering, as the CET program is an undergraduate only curriculum. Faculty sought funding sources for the student research activities, which included LSAMP and Assistantships, to encourage continuing participation. The various experiences in learning, internships and team collaborations provided the student team with a comprehensive understanding of the research development. Using a problem-based learning approach, the faculty team was able to encourage undergraduate researchers to participate in the interdisciplinary project. The diversity of team members' comprehensive knowledge and performance, as a result, resulted in the development of the innovation added to the design and functionality of the R3ER Shelter project. An innovative approach to existing analyses, Sustainability Performance Analysis, was created and utilized to determine best options for the proposed shelters.

Although the initial faculty team did not know what to expect and intended for the team to include multiple disciplines and be interdisciplinary, the project changed over time. The initial team started their work in the fall of 2020, which coincided with the large-scale response to the Covid-19 pandemic. Team meetings were held online or with university social distancing requirements. However, the team found motivation to work on the challenge. Using their individual interests, the team identified an interdisciplinary response to the challenge. The following year, the returning team member with new members, used the DOE feedback and refocused the challenge response. In this case, the team were Final Event Winners, with two members accepting the DOE internships.

References

Abraham, Y. (2020). "*Importance of Active Learning in an Undergraduate Course in Construction Scheduling.*" Paper presented at 2020 ASEE Virtual Annual Conference Content Access, Virtual Online.DOI: 10.18260/1-2--34787

Clary, R., and Wandersee, J. (2010). “Fishbone diagrams: Organize reading content with a "bare bones" strategy.” Science Scope. V.33. N.9. pp. 31-37.

Department of Energy (DOE). (2020). Funding Opportunity Announcement (FOA) Number: DE-FOA-0002196.

Floyd, R. (2019) “*Engineer or Technologist? Which Fits Best?*” Paper presented at 2019 CIEC, New Orleans, LA. https://peer.asee.org/31506

Hallman, S. J., and Chang, B. P. (2020). “*Designing and Evaluating Co-curricular Information Literacy Sessions for Undergraduate Engineering Researchers*. Paper presented at 2020 ASEE Virtual Annual Conference Content Access, Virtual Online . DOI: 10.18260/1-2—34405

Hepworth, M. (2009). “Developing Academic Information Literacy for Undergraduates Through Inquiry-Based Learning.” Innovation in Teaching and Learning in Information and Computer Sciences. V.8. N.2. pp. 2-13. DOI: 10.11120/ital.2009.08020002

Jump into STEM. (2020). <https://jumpintostem.org/challenge/abcmethods/ Retrieved Sept. 18, 2020>

Jump into STEM. (2022). <https://jumpintostem.org/students/> Retrieved June 1, 2022.

Kirkmann, M. and Mosier, R.D. (2022). “Using tools and lessons from online learning to enhance in-person Soil Mechanics Laboratory experiences.” Paper presented at 2022 ASEE Annual Conference & Exposition Minneapolis, Minnesota.

Kpamma, Z. E., Adjei-Kumi, T., Ayarkwa, J. and Adinyira, E. (2016). “An Exploration of the Choosing by Advantages Decision System as a User Engagement Tool in Participatory Design.” Architectural Engineering and Design Management. V.12. N.1. pp. 51–66. DOI: 10.1080/17452007.2015.1095710

Moore, J. D., and Plugge, P. W. (2008). "Perceptions and Expectations: Implications for Construction Management Internships." International Journal of Construction Education and Research. V. 4 N.2 pp. 82-96.

National Science Foundation (NSF). (2022). “Louis Stokes Alliances for Minority Participation.” <https://beta.nsf.gov/funding/opportunities/louis-stokes-alliances-minority-participation> Retrieved June 1, 2022.

Pantoya, M., Hughes, P.C. and Hughes, J.S. (2013) “A Case Study in Active Learning: Teaching Undergraduate Research in an Engineering Classroom Setting” Engineering Education. V.8. N.2. pp. 54-64, DOI: 10.11120/ened.2013.00014

Pinto, M., Caballero Mariscal, D. and Segura, A. (2022). “Experiences of Information Literacy and Mobile Technologies Amongst Undergraduates in Times of COVID. A Qualitative Approach.” Aslib journal of information management. V.74. N.2. pp. 181–201.

Priyadi, A. A., and Suyanto, S. (2019). “The effectiveness of problem based learning in biology with fishbone diagram on critical thinking skill of senior high school students.” Journal of Physics: Conference Series. V.1397. N.1.

Schaub, D., Legg, S., Svoronos, S., Koopman, B., and S. Bai. (1999). “Applying Total Quality Management in an Interdisciplinary Engineering Course.” Journal of Engineering Education. 88:1, 107-112. https://doi.org/10.1002/j.2168-9830.1999.tb00419.x

Siddiqi, K. and Ozcan, S. (2004). ”Construction Management Internship and Co-op Programs: Stakeholder Needs Assessment.” Conference Proceedings, Associated Schools of Construction April 2004.

Schuster, P. and Birdsong, C. (2006). “*Research In the Undergraduate Environment.”* Paper presented at 2006 Annual Conference & Exposition. Chicago, Illinois. DOI:10.18260/1-2–844

Schuster, P., Davol, A., and Mello, J. (2006).”*Student Competitions The Benefits And Challenges*. Paper presented at 2006 Annual Conference & Exposition, Chicago, Illinois. 10.18260/1-2—1055.

An Exploratory Research Study on a University Directed Co-Teaching Initiative with a Community College, High School, and Industry in Support of Aligned Learning Outcomes

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Research has shown that higher education learning, a transition point to industry for most people, is always challenged in meeting the demands of the multidimensional experiences people in practice demonstrate. A greater part of construction related students lack firsthand experience and the required soft skills for industry practice. Thus, a need for a partnership between industry and academia in training students for better learning outcomes is called for. Other studies also project a 9% decline in high school graduation rate between 2020 and 2030, which calls for the need to instill the interest in construction related professions at the high school level to prevent a decline in construction related programs enrolment. The noted challenge has led to the introduction of a co-teaching platform engaging universities, community colleges and high schools, with input from industry, in support of anticipated aligned learning outcomes. This paper presents an exploratory study: a co-teaching initiative involving three instructors of record, six industry practitioners, with the integration of video conferencing technologies (i.e., Zoom Meeting and Meeting Owl Pro), and the effectiveness measured through Direct as well as Indirect Assessment methods. The results demonstrated that students across the various learning platforms were able to meet the set learning outcomes. Survey responses also indicated a good blend between instructors of record and industry practitioners, thereby laying a foundation for the need to continue and improve the co-teaching platform through the online supporting tools to enhance the competencies of young graduates.

Key Words: Teaching with Industry, Meeting Owl Pro, Co-teaching, Aligned Learning Outcomes, Industry Practitioners

Introduction

The educational structure of nations across the globe has always seen reforms that look at improving learning and learners' rights. To this effect higher education institutions see the needed improvements as a quality assurance issue (Adeyeye, 2009) - quality in terms of value for money, fitness of purpose, and student transformation (Biggs, 2001). The evaluation of teaching success should ideally feed into enhancing current and future curricula to ensure relevance for both academic and professional goals. Taking a cue from efforts at achieving quality in the knowledge dissemination process to learners in academia, calls for addressing the disconnect between formal education pedagogy and industry expectations in consonance with mentoring students at the high school level for efficient aligned outcomes. This could only be achieved by one of many ways as taking advantage of the surge in the use of virtual technology platforms for multilateral engagements of all learner groups.

Reiterating the U. S. Bureau of Labor Statistics' future employment projections reported for 2021, it is expected that construction jobs will grow by an estimated 11% nationally between the years 2020 and 2030, which in real numerical terms translates to about 11.9 million additional construction jobs yet to be filled (*Bureau of Labor Statistics News Release*, 2021). These projections serve as a catalyst for carrying out more developmental projects. They also provide an incentive to engage and ~~or~~ train more people who will fill critical positions left vacant or created by the anticipated job growth.

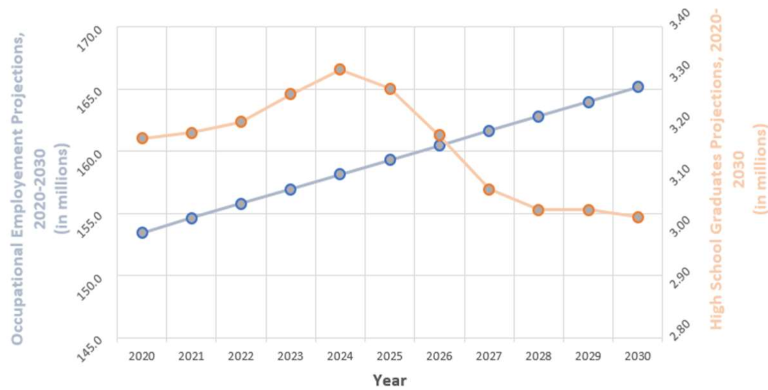

Figure 1. Graph of Projected Increase In Construction Workforce Vs Projected Decline in High School Graduation Across the US, 2020 – 2030

Despite the projected positive trend in total employment, the Western Interstate Commission for Higher Education (WICHE) by their 2017 report, is also predicting a 5% rise in the number of high school graduates through year 2025, followed by a sudden 9% drop in 2026 and beyond (see figure 1) (*Knocking at the College Door*, 2021). This reality raises a lot of concern especially when no measures seem to be in place to meet the demands of the projected boom in construction jobs. To add to this, a 2016 Gallup Student Poll found out that student engagement in school drops swiftly from 5th grade through 12th grade. It suggests that about three quarters of elementary school kids (76%) are found to be engaged in school, while only 44% of high school kids truly get engaged. Which translates to, fewer students getting engaged as they progress through school (Brenneman, 2016). "With each year that these students progress in school, not engaging with their dreams and thus becoming less engaged overall, the more our hopes of long-term economic revival are dashed" (Busteed, 2013). It therefore behooves construction educators to seek a unifying platform that embraces all stakeholders to connect through a common source of information sharing (i.e., a well-planned schedule to engage physically or by videoconferencing modes).

Recent studies into the use of Zoom for course delivery have found out that the Zoom Meeting platform supports the use of a virtual white board with annotation capacity to explain concepts, formation of breakout rooms to create small collaborative group work, solicit feedback from students through polls, and multi-way chat to facilitate class discussions. In addition, Zoom meetings can be recorded and made available for future reference (Vandenberg & Magnuson, 2021). Thereby making it a good fit for administering course content in construction safety requirements (Nnaji & Krachan, 2020). Another positive is it aids co-teaching, which to a larger extent touches many more diverse student groups and is far reaching (Brendle & Lock, 2017).

This paper explores the effectiveness of co-teaching platforms with industry undertaken across University of Wyoming, Casper Community College, and Pathways Innovation Center in support of aligned learning outcomes. The findings of which will justify the need for continuation and improvement of a virtual learning platform (i.e., Zoom Meeting & Meeting Owl Pro); an online tool supporting the need to bridge the disconnect between industry and academia and also meet the expectations of industry when recruiting for open positions.

Literature Review

The concept of co-teaching described in many forms is an enhancing charter for student learning outcomes, and to partner with industry practitioners in this novelty with the supporting medium for information sharing, pushes for a lasting innovation. The themes: "Co-Teaching and its Use across Multiple Teaching Platforms," "Teaching with Industry" (TWI) and Student Learning Outcomes" (SLO's) which sum up the research study are further reviewed in the proceeding sections.

Co-Teaching and Its Use across Multiple Teaching Platforms

Co-teaching is defined as having two or more people share the responsibility for teaching some or all of the students assigned to a classroom (Villa et al., 2008). It is one form of teaching where there is diversity in shared knowledge base is, and students benefit a lot from it (Walters & Misra, 2013). A test of this is illustrated in this study, where three instructors of record collaborated with industry practitioners in co-teaching a Construction Safety class.

Different forms of co-teaching models have been identified by several studies and grouped into six main models (Potts & Howard, 2011), which are "One teach, One observe," "One teach, One assist," "Parallel Teaching," "Station Teaching," "Alternative Teaching," and "Team Teaching". Each one of these co-teaching models is driven by its strength and in each case, all instructors are selected certified professionals although each may have their specific areas of expertise. This research study adopted the team-teaching model. In essence seeking to model a collaborative process within the classroom. Through this form of co-teaching, more students appreciate and assimilate better how theories and concepts are shared and or argued differently through several unique perspectives by co-instructors (Harris & Harvey, 2000). The experience influences students' appreciation for collaboration and negotiation in collaborative relationships that form part of their professional workplace training.

Teaching with Industry (TWI)

As introduced above, the missing expected graduate qualities such as their lack of soft/transferable skills, essential in today's labor market is predominantly discussed within current literature. Employers have blamed and criticized higher education institutions for not preparing students adequately for the current labor market, and thus continuously highlight students' lack of transferable skills (Hurrell, 2016). The phenomenon raises the question as to whether the soft/transferable skills gap, identified by employers, should be attributed to higher education institutions, that may be missing out on the right strategy, or to the graduates and employers themselves who may be adopting inadequate recruitment and graduate development processes (Griffiths et al., 2018). It is acknowledged that academia and industry collaboration is essential to address the challenges both academia and industry are facing in adopting and promoting emerging technology in the construction industry. A successful collaboration between academia and industry can promote the commercialization of emerging technology, and again academia can benefit from the industry, which provides emerging technology research needs and additional funding to researchers (D'Este & Perkmann, 2011). A good innovative collaboration between academia and industry definitely leads to enriching student learning outcomes, and in order to measure this, the study has invited six industry practitioners to help teach the content as it relates to their industry experiences.

Student Learning Outcomes (SLO's)

The effectiveness of every academic program leading to the award of a diploma, or certain student support programs are measured through the use of student learning outcomes (SLO's). These SLO's are described as the knowledge, skills, and abilities that a student attains after going through a particular set of higher education experiences. One significant characteristic of student learning outcomes is that it is very specific and measurable; the results and analysis of the measurable should lead to a continuous chain of improving the taught course of study.

The education system in the USA currently requires that a lot of innovation be implemented to produce the needed learning outcomes at all school levels. The focus of educating future generations should be geared towards a combination of learning theory and practice without ignoring the expectations of the learners and the societies being affected directly. Instructors who will be engaging these students will therefore need to be sensitive to the expectations of students to maximize their learning experiences (Mupinga et al., 2006). The Bloom's Taxonomy scale (see figure 2), developed by Benjamin Bloom and revised by Anderson, Krathwohl puts the development of learning in perspective in that the sequence of learning must follow the Blooms hierarchy. This is required to plan and deliver integrated course content that leads to students operating at more complex levels of thinking (Ferguson, 2002). The information presented in this paper, which is part of a larger research study, follows through a cyclic methodology framework described in detail in the following section.

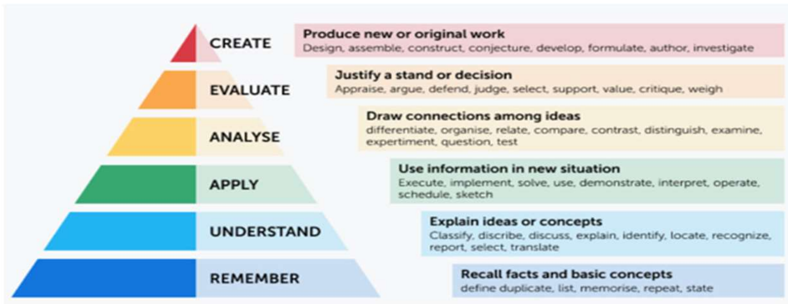

Figure 2. Bloom's Taxonomy Scale(*Bloom's Taxonomy*, 2022)

Research Methodology

The study, carried out by the newly established Construction Management program at the University of Wyoming, was developed with a methodology framework outlined in four levels (figure 3) and through a 16 week period across three campuses that engaged three instructors of record, their respective students (i.e., University of Wyoming, Casper Community College, and Pathways Innovation Center) as well as invited industry practitioners.

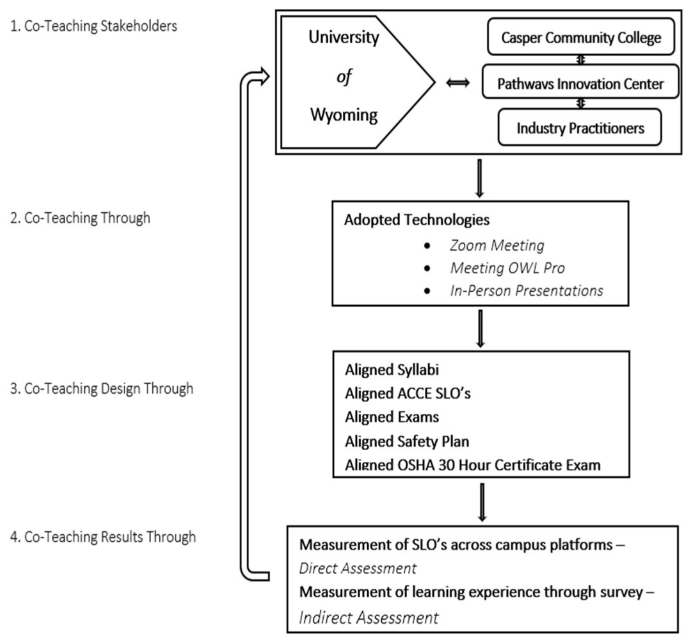

Figure 3. Methodology Framework of Research Study

The enrolled students for the Construction Safety (CM 2300) course, the course used for the study, included 27 students from University of Wyoming, nine students from Casper Community College and 14 students from Pathways Innovation Center (i.e., High School). The expertise of six industry practitioners were sought in aligning to the objectives of the study. Each of the industry practitioners were selected based on their industry specialty as it related to Construction Safety and with help from the Industry Advisory Board (IAB) and statewide industry associations. Two videoconference technologies were identified and integrated as part of the teaching platform: Zoom Meeting and Meeting OWL Pro device. These technologies were used in tandem with the original set up of the classroom which embodied in-person presentations and the flexibility of integrating synchronous communication through audio and visual data. The classroom setup (see figure 4) was laid out with students seated round tables arranged in an array throughout the classroom to enable in-class group activities. Each lecture session had students shuffled to avoid the same students forming clusters. Within each student sitting groups, open-ended questions pertaining to topics delivered by the instructor of record and or the industry practitioner are discussed.

Figure 4. Typical Classroom Setup with an Industry Practitioner during One of the Lecture Presentation Sessions

Study Results

The study results were defined under two categories, Direct and Indirect Assessments. The first category assessed the output of student learning through administered quizzes and safety plans while the second category focused on the analyses of the output data from surveys administered to instructors of record, industry practitioners and students. The data collated for both categories of assessment were analyzed with SPSS and graphs plotted for a better comparison.

Direct Assessment

The first measure of student learning outcomes (i.e., Direct Assessment) was assessed through the administering of three quizzes as well as in-class discussion questions. The quizzes consisted of multiple choice and true or false questions drawn from the textbook chapters for the Construction Safety course. In addition, each student was tasked with developing a Construction Safety Plan and the grades collated and statistically analyzed.

Interpretation of Descriptive Results for Quizzes and Safety Plan

In Quiz 1, the mean grade scored by students at Casper Community College (M = 82.78, SD = 4.66) was the highest compared to the average grade scored by University of Wyoming students (M = 70.7, SD = 6.78) and Pathways Innovation Center (M = 80.25, SD = 11.71) (figure 5). However, the computed standard deviations showed that variability in the graded scores for Casper Community College was low compared to variability in grades recorded for University of Wyoming and Pathways Innovation Center students. Also, Quiz 2 presented about the same trend in the average recorded grades for all three institutions. The mean grade scored by students from Casper Community College (M = 82.88, SD = 8.56) was the highest compared to the average grade scored by University of Wyoming students (M = 65.93, SD = 5.17) and Pathways Innovation Center (M = 80.25, SD = 10.17). Variability in the graded scores was low for University of Wyoming students compared to variability in graded scores for Casper Community College and Pathways Innovation Center.

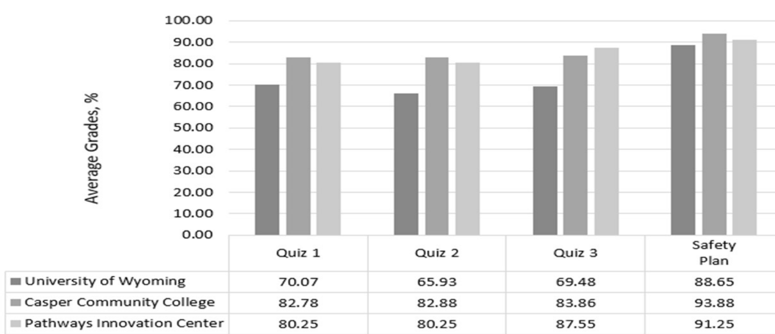

Figure 5. Direct Assessment of Grades of Quizzes and Safety Plan across the Three Campuses

The third and final quiz for the study recorded a different trend in the average grades of students across the three institutions. Pathways Innovation Center (M = 87.55, SD = 11.89) averaged a higher quiz grade relatively to Casper Community College (M = 83.86, SD = 6.07) and University of Wyoming (M = 69.48, SD = 4.09). There was low variability in the graded scores for University of Wyoming compared to variability in graded scores for Casper Community College and Pathways Innovation Center. The computed standard deviations confirm this. Pathways Innovation Center saw high variability in the graded scores for Quiz 3. On the other hand, grades reported for the developed Safety Plans saw the average grade from students of Pathways Innovation Center (M = 91.25, SD = 2.81) relatively higher than the average grades of students from University of Wyoming (M = 88.65, SD = 6.74) and Casper Community College (M = 83.44, SD = 3.68). There is also relatively high variability in the grades from University of Wyoming compared to the grades from Pathways Innovation Center and Casper Community College.

Indirect Assessment

End-Course Survey Administered to Students

Indirect assessment of the co-teaching platform with industry practitioners and how effective it was on the set learning outcomes was done by collecting data that required students' ratings of the "Co-Teaching Platform Technology," "Instructor Support and Collaboration," "Industry Practitioners' Support," and "Students' Learning Outcome". A total of 27 students from University of Wyoming took the survey, thus recording a 100% participation rate; seven students out of the total 9 enrolled students in Casper Community College also took the survey, reporting 77.7% participation rate while eight enrolled students from the recorded 14 from Pathways Innovation Center participated in the survey, giving a participation rate of 57.14%. Two students out of the eight who took the survey in Pathways Innovation Center did not complete the survey. Thus, giving a 75% completion rate. All the students from University of Wyoming and Casper Community College who were engaged in the survey completed fully and successfully, keeping a 100% completion rate for both campuses.

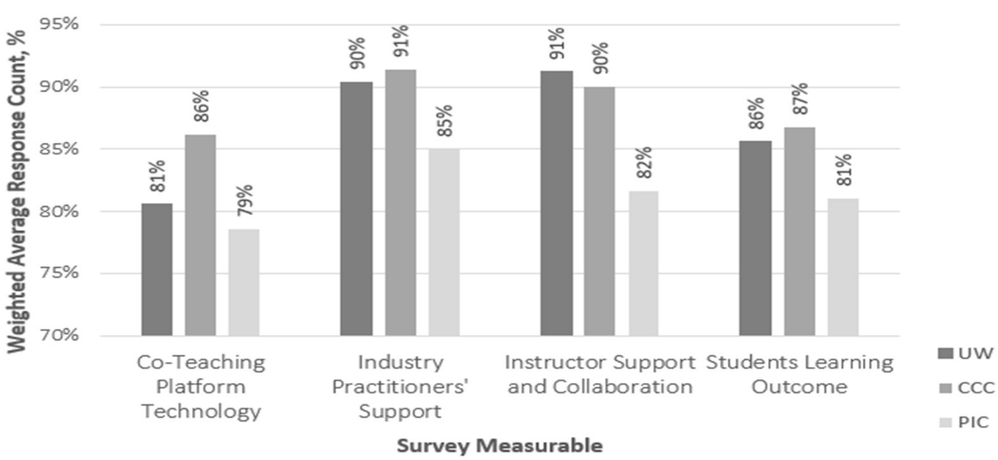

Figure 6. Graphical Representation of Mean Response Count of Survey Measurable (i.e., University of Wyoming, Casper Community College, and Pathways Innovation Center)

According to the graph of collated responses (figure 6), the weighted averaged response count for all the questions asked represented generally positive feedback. For instance, the questions rating "Instructor Support and Collaboration" had a response pattern of 82% for Pathways Innovation Center which suggested positive feedback 91% for University of Wyoming and 90% for Casper Community College, both also representing positive feedback.

Similarly, the response pattern for the questions rating the "Students' Learning Outcome," showed 86% for University of Wyoming, 87% for Casper Community College and 81% for Pathways Innovation Center. These weighted averaged response counts depicted positive feedback also.

End-Course Survey Administered To Instructors of Record

The assessment of the co-teaching platform with industry practitioners for the aligned learning outcome was again done by collecting data that required instructors of record to rate the "Co-Teaching Platform Technology," "Instructor

Support and Collaboration," "Industry Practitioners' Support," and "Students' Learning Outcome". Results from the survey administered to instructors of record showed a 100% participation and completion rates.

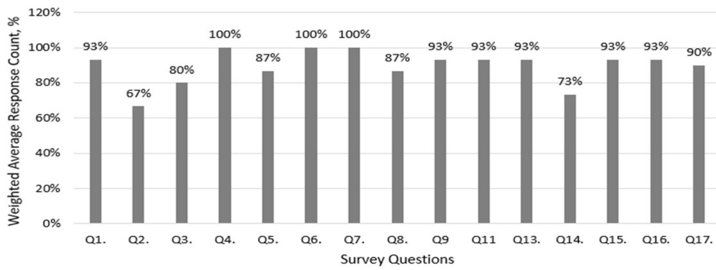

Figure 7. Graphical Representation of Weighted Average Response Count from Instructors of Record

A general overview of the response pattern from the instructors of record (figure 7) illustrated that more than 80% of the survey questions received positive feedback. For example, the weighted averaged response from Questions 4, 6 and 7 were overwhelming positive feedback. Typically Question 4 rated the level of collaboration amongst the instructors and industry practitioners (i.e., Industry Practitioners' Support") and the weighted averaged response count was 100% ("Very easy"), while Question 7 rating the level of contribution industry practitioners introduced to the learning platform (i.e., "Industry Practitioners' Support"). And the weighted averaged response count was 100% ('Excellent").

Again, Questions 9, rated the comfort level with the technology (Zoom Meeting and Meeting Owl Pro) for teaching across campuses (i.e., "Co-Teaching Platform (Technology)"), and the response was that of positive feedback ("Easy" to "Very Easy").

End-Course Survey Administered To Industry Practitioners

Out of the nine Likert-scale questions administered to the industry practitioners, seven questions (i.e., Questions 1, 3, 4, 5, 6, 7 and 9) had positive feedback (figure 8). Each question tested one of the measurable "Co-Teaching Platform (Technology)", "Instructor Support and Collaboration," "Industry Practitioners' Support," and "Students' Learning Outcome". The response to Question 1, rating how well industry practitioners thought they connected with students during their presentation (i.e., "Co-Teaching Platform (Technology)") received a 90% measure ("Extremely well"), showing industry practitioners connected positively with students. There was a 60% measure ("About what I expected") with Question 8, which rated if the class period allowed ample time to teach the prepared lecture content.

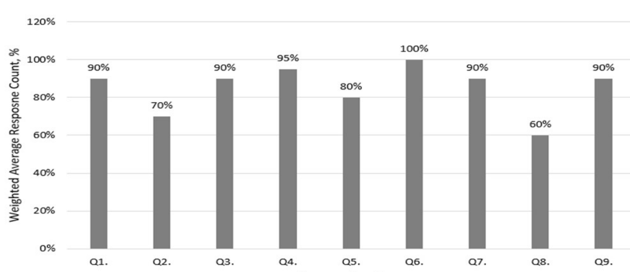

Figure 8. Graphical Representation of Weighted Average Response Counts from Industry Practitioners

Conclusion

This study explored co-teaching platforms with industry, and its effectiveness on aligned learning outcomes. Direct assessment of the students in the CM 2300: Construction Safety course, showed that the average grades obtained for all three quizzes and safety plans ranged from A to C, showing students understood the knowledge of industry vernacular & construction content, knowledge of OSHA and industry safety standards and were able to develop construction project safety plans, which is a requirement for future industry practice. End-course surveys administered to indirectly assess the "Co-Teaching Platform (Technology)," "Instructor Support and Collaboration," "Industry

Practitioners' Support," and "Students' Learning Outcome" all generally polled positive feedback. Instructors of record worked together tirelessly to achieve a good collaborative blend. This teaming effort between University of Wyoming, Casper Community College, Pathways Innovation Center, and industry practitioners could be seen as one of the deciding factors on students' readiness to engage in another co-teaching with industry support in the future (77% for University of Wyoming, 90% for Casper Community College and 80% for Pathways Innovation Center representing "Definitely yes").

Taking into consideration the predicted 9% decline in high school graduates, between year 2026 and 2030, which has the tendency to negatively impact workforce, it is imperative that an initiative was taken now to add more professionals to the pool of construction workers. By diligently following through a well laid out curriculum supported by industry practitioners and sourcing for good technology like Zoom Meeting and Meeting Owl Pro that connects all participants irrespective of where they are located, a lot more successes could be achieved. The authors also acknowledge that the study needs to be expanded to more courses in the curriculum run by the Construction Management programs. Additional direct and indirect assessment data could be collected so that more improvements can be made to the teaching model, as more appropriate measures and methods of assessment are introduced. Also, the study should be generalized to solicit for information from industry experts and educators in other fields apart from those in the construction sector.

References

Adeyeye, K. (2009). Teaching construction contracts: Mutual learning experience. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction*, *1*(2), 97–104. https://doi.org/10.1061/(asce)1943-4162(2009)1:2(97)

Biggs, J. (2001). The reflective institution: Assuring and enhancing the quality of teaching and learning. *Higher Education, 41*, 221–238. https://doi.org/10.1023/A:1004181331049

Bransberger, Peace. "Impact and Implications: Projections of Male & Female High School Graduates. Wiche Insights." *Western Interstate Commission for Higher Education*, Western Interstate Commission for Higher Education. Http://Wiche.edu, 31 Aug. 2017, https://eric.ed.gov/?id=ED586771

Brendle, J., Lock, R., & Piazza, K. (2017). A Study of Co-Teaching Identifying Effective Implementation Strategies. *International Journal of Special Education*, *32*(3). https://doi.org/https://files.eric.ed.gov/fulltext/EJ1184155.pdf

Brenneman, R. (2021, April 27). *Gallup student poll finds engagement in school dropping by grade level*. Education Week. https://www.edweek.org/leadership/gallup-student-poll-finds-engagement-in-school-dropping-by-grade-level/2016/03

Busteed, B. (2020, March 13). *The school cliff: Student engagement drops with each school year*. Gallup.com. https://news.gallup.com/opinion/gallup/170525/school-cliff-student-engagement-drops-school-year.aspx

D'Este, P., & Perkmann, M. (2010). Why do academics engage with industry? The entrepreneurial university and individual motivations. *The Journal of Technology Transfer*, *36*(3), 316–339. https://doi.org/10.1007/s10961-010-9153-z

Ferguson, C. (2002). Using the revised taxonomy to plan and deliver team-taught, integrated, thematic units. *Theory Into Practice*, *41*(4), 238–243. https://doi.org/10.1207/s15430421tip4104_6

Griffiths, D. A., Inman, M., Rojas, H., & Williams, K. (2018). Transitioning student identity and sense of place: Future possibilities for assessment and development of Student Employability Skills. *Studies in Higher Education*, *43*(5), 891–913. https://doi.org/10.1080/03075079.2018.1439719

Harris, C., & Harvey, A. N. (2000). Team teaching in Adult Higher Education classrooms: Toward Collaborative Knowledge Construction. New Directions for Adult and Continuing Education, 2000(87), 25–32.

https://doi.org/10.1002/ace.8703 Heckman, J., & Kautz, T. (2012). Hard evidence on Soft Skills. https://doi.org/10.3386/w18121

Hurrell, S. A. (2015). Rethinking the soft skills deficit blame game: Employers, skills withdrawal and the reporting of Soft Skills Gaps. *Human Relations*, *69*(3), 605–628. https://doi.org/10.1177/0018726715591636

Mupinga, D. M., Nora, R. T., & Yaw, D. C. (2006). The learning styles, expectations, and needs of online students. *College Teaching*, *54*(1), 185–189. https://doi.org/10.3200/ctch.54.1.185-189

Nnaji, C., & Karakhan, A. A. (2020). Technologies for safety and Health Management in construction: Current use, implementation benefits and limitations, and adoption barriers. *Journal of Building Engineering*, *29*, 101212. https://doi.org/10.1016/j.jobe.2020.1012122

Potts, E. A., & Howard, L. A. (2011). How to co-teach: A guide for general and special educators. Paul H. Brookes Publishing.

"Projections Overview and Highlights, 2020–30: Monthly Labor Review." *U.S. Bureau of Labor Statistics*, U.S. Bureau of Labor Statistics, Oct. 2021, https://www.bls.gov/opub/mlr/2021/article/projections-overview-and-highlights-2020-30.htm

Villa, R. A., Thousand, J. S., & Nevin, A. (2008). *A guide to co-teaching: Practical tips for facilitating student learning*. Corwin Press.

Walters, K., & Misra, J. (2013). Bringing collaborative teaching into doctoral programs: Faculty and graduate student co-teaching as experiential training. *The American Sociologist*, *44*(3), 292–301. https://doi.org/10.1007/s12108-013-9185-6

HVAC Mechanical Contractors Framework for Effective Project Close-Out

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Project close-out activities and the transfer of information to the general contractor and owner are critical steps in meeting desired project outcomes and receiving timely final payments. This process, when not planned for, leads to delays and challenges that can harm a project's profitability and overall owner satisfaction. HVAC contractors are one of the major trades on construction job sites responsible for providing important facility operational information. If their close-out processes are not effective, they not only threaten their internal project success but can cause prolonged delays for other project stakeholders. This paper discusses a framework for project close-out for HVAC mechanical contractors. The research developed and analyzed fourteen (14) case studies documenting different companies' close-out processes. This allowed for identifying common challenges and existing workflows to determine how various companies addressed those challenges. The study resulted in a framework, represented as a process model workflow, to help HVAC mechanical contractors improve their internal close-out processes.

Key Words: Close-out, HVAC mechanical contractor

Introduction

The Project Management Institute (PMI) (2008) formally defines "project closing" as the process of concluding all activities to formally complete the project, phase, or contractual obligations. Project close-out is typically the final stage of a subcontractor's project responsibilities. The project team demobilizes, documents are archived, punch list items are completed, and the project is handed over to the client. Project close-out in the construction industry has been challenging as the close-out process often lingers past project completion. According to Shay (2019), project stakeholders incur associated costs from this delay, such as construction loan interest, employee wages and benefits, insurance, and rental fees.

One of the critical scopes of work on any project is the mechanical systems. Over 12% of the overall project cost in the United States is attributable to mechanical systems (Ford, 2020). For more complex jobs, like healthcare facilities, laboratory buildings, and data centers, mechanical systems account for significantly more of the overall project budget. In this respect, mechanical contractors play a significant role in the overall project success. Additionally, the mechanical systems are substantial to the function of the building by providing a healthy indoor environment (Simpeh et al., 2021). The efficiency of the mechanical system impacts overall energy consumption, which is influenced by faults in installation, system balancing, and ductwork leakage (Mirnaghi and Haghihat, 2020). Part of the close-out process is to verify the quality of these systems installed, document the efficiency of how these systems are running, and fine-tune the startup of the equipment (O'Connor and Mock, 2019). HVAC mechanical contractors have identified challenges to efficiently and effectively completing close-out tasks supporting the general contractor and owner's project needs (Magxaka et al., 2022).

This study aimed to identify a currently utilized process that can help HVAC mechanical contractors efficiently close out a project and successfully meet expected outcomes for the project. The research documented practices from various companies by developing case studies that were analyzed for challenges and practices utilized to overcome those challenges. The close-out processes used by these companies were documented as a workflow and analyzed for differences in how the companies addressed identified problems. From this comparison, a framework to support effective project close-out that addressed the identified challenges was proposed. That framework is discussed in detail in this paper.

Literature Review

Closing out a project successfully goes beyond meeting budget and schedule constraints and relies heavily on meeting the owner's expectations of quality and service (Arantes and Ferreira, 2021). Since subcontractors are primarily responsible for performing 80-90% of the work, their performance heavily influences overall project success (Keshavarz-Ghorabaee et al., 2018). One way that many subcontractors meet project requirements is through project controls. These project controls often help gauge how a company utilizes its resources in generating successful project outcomes in closing out the project (Demirkesen & Ozorhon, 2017). Project controls go beyond budget and schedule tracking to reviewing quality periodically throughout the project. Common quality control activities utilized in construction for the close-out are the production of QA/QC reports and punch lists on behalf of the general contractor and/or owner (Vaughan et al., 2013). The timely receipt and completion of addressing issues on these reports and lists commonly result in project close-out delays (Tummalapudi et al., 2022).

Other factors that affect project close-out have been identified as coordination issues between trades, leading to design document flaws, slow change order approvals, and late payments (Gunduz & Elsherbeny, 2020). The handover of as-built construction documents and other building information to the owner is crucial to support the operations of the facility, however, it is often overlooked or poorly implemented (Zhu and Xu, 2021). Close-out requirements are often unclear with substandard contract clauses that do not effectively address the owner's desires or operational expectations for the roles and responsibilities of collecting the information. This leads to a lack of urgency from project participants to internally produce documents until requested closer to the end of the project, causing close-out delays (Arantes & Ferreira, 2021). Due to procedural issues, project close-out is not always successful (Hansen, 2021). Most project close-out challenges stem from human interactions and conflict among project stakeholders (O'Connor et al., 2019).

Current literature provides recommendations to mitigate project close-out challenges. Larsen et al. (2017) state that commissioning can reduce budget and time overruns by increasing early planning and organizational support, resulting in higher-quality technical systems and better end-user satisfaction.

Independent QA/QC professionals are recommended for effective commissioning, testing, and balancing (Mock & O'Connor, 2019). Johnson et al. (2017) suggest assessing techniques to improve final close-out documentation preparation, lowering the time designated for material checks, and establishing an internal task force to examine the organization's project close-out process. Other options include reducing paperwork using centralized and secure document management solutions, standardizing checklists (Johnson et al., 2017), and integrating a building operations expert at the design and construction stage to identify appropriate documentation needs (Elzarka, 2009).

However, the current literature does not provide any close-out processes that HVAC contractors in the construction industry are currently utilizing. This study fills an important gap in the literature by documenting such processes from various HVAC contractors.

Methodology

The research aims to examine current workflows utilized by various HVAC mechanical sub-contractors to determine methods to address challenges during the project close-out processes. This was accomplished through a multiple case study analysis. The fourteen (14) case studies were developed utilizing semi-structured interviews. These interviews took place over Zoom, a web conferencing platform, and took between sixty (60) and ninety (90) minutes. The interviewees represented fourteen (14) different companies from across the United States, with one working internationally in Canada. The participants were in leadership positions (owner/president, vice-president, or senior project manager) within their respective companies. They knew the overall company policies and processes related to project close-out. To develop the case studies, the interviews were recorded and transcribed. The transcriptions were then coded through a constant comparison analysis allowing for iterative analysis of initial codes and secondary codes and eventually identifying overarching themes. QDA Miner Lite was used to support the coding analysis. The themes that emerged were either challenges, close-out strategies, or success measures. These thematic findings were previously published (Magxaka et al., 2022). As a follow-up to the initial part of the research, the study discussed in this paper reviewed the developed case studies and analyses of the individual workflows to propose a framework that HVAC mechanical subcontractors can use to improve their internal close-out processes. The case studies were reviewed to identify challenges faced by each company and then they were cross-analyzed with other case studies that did not report those same challenges. This multiple case-study analysis resulted in the proposed framework that is discussed below.

Proposed Framework for Effective Project Close-out

Based on the case study analysis findings, activities that support project close-out were identified. These activities are based on processes identified throughout the case studies to support successful close-out. The workflow in the framework is organized based on the project lifecycle phase. The intended use of the framework is to allow companies to review their processes and evaluate where they might be able to improve. Common challenges that these strategic activities can help a company address include issues with communication, long (and delayed) punch-lists from other project stakeholders, unclear operational expectations in terms of document needs, schedule delays and conflicts resulting from change orders, document submittal delays, and challenges related to early demobilization. The activities incorporate strategies of identifying accountability, pre-planning, use of internal checklists, applications of lessons learned, and actively scheduling milestone meetings to help overcome the challenges. Figure 1 shows the proposed framework.

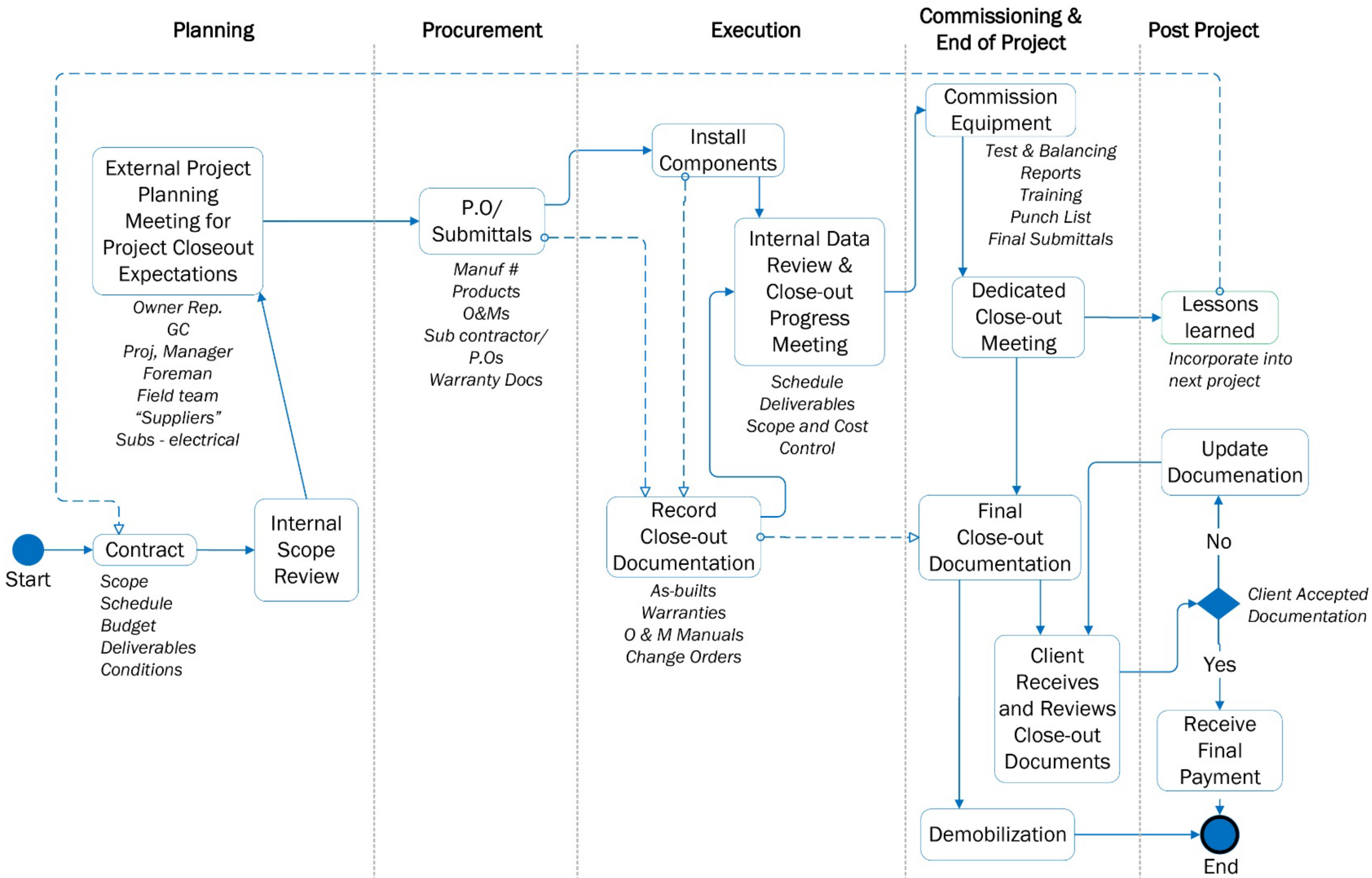

Figure 1: Mechanical Contractor Close-out Process

Not all companies in the case studies utilized all the activities, this workflow depicts a compilation of practices from a compiled review of industry practices. The incorporation of any of the included activities may be influenced by company size, the scope of the project, and the required project deliverables.

Planning Phase

Successful project close-out greatly depends on the planning of the project as to how close-out activities are handled. The case studies revealed two processes that helped to set the project up for success. They both involve setting up appropriate operational expectations internally and externally with other project stakeholders. Those practices include the use of an internal scope review meeting and a project-planning meeting with external stakeholders.

1. *Contract/Internal Scope Review* – During the planning phase, the mechanical contractor's project team reviews the scope, schedule, budget, deliverables, and other contractual obligations related to project close-out. This meeting includes identifying internal checklists for QA/QC, setting milestones for supplying needed information, and determining project team responsibilities.
2. *External Project Planning Meeting* – This meeting is held with all the key stakeholders (internal and external) to understand the expectations and responsibilities related to project close-out documentation. Scope, schedule, budget, and deliverables are discussed and finalized with external partners. A key stakeholder, such as the owner rep and/or facility manager, that will be responsible for approving the project close-out package is identified. The owner's requirements and expectations regarding project close-out are identified, documented, and communicated proactively with the project team.

Procurement

A lot of information about the equipment utilized in the building becomes available during the procurement phase of the project in the form of purchase orders and submittals. In many cases, owners require information about mechanical equipment to be documented in specific ways and provided at close-out. One method for promoting a more effective project close-out is to document this information when it becomes available. During the procurement phase, information related to the model numbers, material data samples, and O&M manuals can be proactively collected and organized in preparation for document close-out.

Execution

Throughout the execution phase, information should be documented as it becomes available. This includes recording serial numbers and model numbers of equipment, changes to the drawings in producing as-built drawings, documenting approved change orders, maintaining an ongoing punch list of QA/QC activities and resolving them early, and compiling warranty information.

This information can then be reviewed during internal data review and close-out meetings. These meetings are where close-out documentation is checked throughout the execution phase by the management team and field team to discuss project status in terms of schedule, scope, cost control, and final deliverables.

Commissioning and End of Project

During commissioning, the mechanical contractor facilitates the commissioning and startup of equipment, generating testing and balance reports, facilitating owners' training for successful equipment operation, resolving final punch list items, and compiling final submittals to turn over to the general contractor and owner. Once these are collected, a dedicated close-out meeting is conducted internally with the project team to discuss all aspects of the close-out documents and ensure they are complete and accurate before submitting them to the client. The finalized documents are then submitted for client review. Once this is completed, the team demobilizes and moves on to other projects.

Post Project

After each project, it is important to identify lessons learned, document them, and incorporate them into future projects. Some information to consider during these lessons learned process include documentation requirements, the success of meeting those requirements, number and types of meetings and their effectiveness, nature of the type of owner and client relationships, payment time with contractor and vendors, approval time, internal team improvements, and overall close-out process improvements that can help on the next project. The lessons learned should be formally documented and shared with other project team leaders within the company.

Also, closely following the end of the project, the client should be provided a timeline to review the final close-out documents and request changes if necessary. These changes are easier to identify closer to the end of the project as possible, so information is not lost. The review of these documents often influences the final payment from the client as it may be withheld until any issues with the close-out documents are resolved.

Discussion

For a company to take advantage of the findings of this research, it would need to review and benchmark its current processes and identify what challenges they need to address. To do this, key project team participants would need to be recognized that can review current documented close-out process protocols, if they exist. A benchmarking process to support this process includes the following steps:

1. Interview the key project team participants to identify different project close-out processes utilized by various team members within your company.
2. Compare the different close-out processes utilized from the interview and create a workflow of the typical close-out process used within the company. If a documented close-out process exists, check for compliance and effectiveness between the documented and implemented processes. Many companies identify having "understood" or formal processes but admit they are not followed.
3. Compare the findings from the internal company investigation and mapping to the proposed framework discussed earlier.
4. Identify activities from the proposed close-out process that may be appropriate for the company to implement based on the project scope, project size, and company size.
5. Update or create a documented close-out process for the company.
6. Disseminate, educate, and train on the process and then track effectiveness. It is important to revisit the process, ensure it is working as planned, and make appropriate adjustments.

Conclusion

This paper discusses one phase of the research project that examined close-out practices utilized by HVAC mechanical subcontractors. As part of the research, case studies were developed documenting fourteen (14) companies' close-out processes. These cases were each documented in a workflow diagram and then cross-analyzed to identify how identified various companies were addressing common challenges. The identified processes were compiled into a proposed framework to help reduce the effect of challenges on closing out a project. This research addresses current challenges that mechanical contractors are experiencing in effectively and efficiently closing out projects.

The recommendations made from this study were specific to mechanical subcontractors. The general concept behind the framework is likely generalizable to other sectors of the industry, however, this would need to be reviewed in future research. It is reasonable to hypothesize that similar challenges in terms of timely and successful project close-out would be found in other industry sectors, however, some are specific to the mechanical contractors based on the types of equipment and work they are responsible for. Future studies will also include evaluating the proposed framework's effectiveness with companies implementing the findings.

References

Arantes, A., & L.M.D. Ferreira. 2021. "A methodology for the development of delay mitigation measures in construction projects." *Production Planning & Control: The Management of Operations.* 32 (3), 228-241. https://doi.org/10.1080/09537287.2020.1725169

Demirkesen, S., & B. Ozorhon. 2017. "Measuring project management performance: Case of construction industry." *Eng. Manage. J.*. 29 (4), 258-277. https://doi.org/10.1080/10429247.2017.1380579

Elzarka, H. M. 2009. "Best practices for procuring commissioning services." *J. Manage. Eng.* 25(3), 155-164. https://doi.org/10.1061/(ASCE)0742-597X(2009)25:3(155)

Ford, C. 2020. Cost of Constructing a Home. NAHB Economics and Housing Policy Group. https://www.nahb.org/-/media/8F04D7F6EAA34DBF8867D7C3385D2977.ashx

Gunduz, M., & H.A. Elsherbeny. 2021. "Critical Assessment of Contract Administration Using Multidimensional Fuzzy Logic Approach." *J. Constr. Eng. Manage.* 147(2), 04020162. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001975

Hansen, D. E. 2021. "Including Commissioning During Design Phase Benefits New Construction: a Qualitative Case Study." Doctoral dissertation, La Jolla, CA: Northcentral Univ.

Johnson, T. A., D.A. Michaels, R.E. Sturgill Jr. & T.R. Taylor. 2017. "Streamlined project close-out for construction at KYTC" (No. KTC-17-12/SPR13-460-1F). Kentucky Transportation Center, University of Kentucky, Lexington, KY. https://doi.org/10.13023/KTC.RR.2017.12

Keshavarz-Ghorabaee, M., Amiri, M., Zavadskas, E. K., Turskis, Z., & Antucheviciene, J. (2018). A dynamic fuzzy approach based on the EDAS method for multi-criteria subcontractor evaluation. *Information*, 9(3), 68. https://doi.org/10.3390/info9030068

Larsen, J. K., S.M. Lindhard, T.D. Brunoe, & K.N. Jensen. 2018. "The relation between pre-planning, commissioning and enhanced project performance." *Construction Economics and Building.* 18(2), 1-14. https://doi.org/10.5130/AJCEB.v18i2.5762

Magxaka, M, D. Gajjar, & J. Lucas. 2023. "Project Close-Out Process for HVAC Mechanical Contractors: Current Practices." *Journal of Construction Engineering and Management*. 149(2), https://ascelibrary.org/doi/abs/10.1061/JCEMD4.COENG-12394

Mirnaghi, M. S., & F. Haghighat. 2020. "Fault detection and diagnosis of large-scale HVAC systems in buildings using data-driven methods: A comprehensive review." *Energy Build. 229*, 110492. https://doi.org/10.1016/j.enbuild.2020.110492

Mock, B., & J.T. O'Connor. 2019. "High-value, low-effort industrial plant commissioning solution strategies." *Construction Innovation*. 19(4), 653-671. https://doi.org/10.1108/CI-09-2018-0072

O'Connor, J. T., & B.D. Mock. 2019. "Construction, commissioning, and startup execution: Problematic activities on capital projects." *J. Constr. Eng. Manage.* 145(4), 04019009. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001621

Project Management Institute, Inc. (PMI). 2008. *A Guide to the Project Management Body of Knowledge (PMBOK Guide), 4th ed*. (Newtown Square, PA: Project Management Institute, Inc., 2008), 11–16.

Simpeh, E. K., J.P.G. Pillay, R. Ndihokubwayo, & D.J. Nalumu. 2021. "Improving energy efficiency of HVAC systems in buildings: A review of best practices." *International Journal of Building Pathology and Adaptation*, *40*(2), 165–182. https://doi.org/10.1108/ijbpa-02-2021-0019

Shay, Z. B. 2019. "Factor that affect construction project close-out delay in 40/60 saving house project of Addis Ababa." Doctoral dissertation, Ethiopia: Addis Ababa Science and Technology Univ.

Tummalapudi, M., M. Harper, C., Taylor, T. R., Waddle, S., & Catchings, R. (2022). Causes, Implications, and Strategies for Project Closeout Delays in Highway Construction. *Transportation Research Record*, 03611981221087229. https://doi.org/10.1177/03611981221087229

Vaughan, J. L., Leming, M. L., Liu, M., & Jaselskis, E. (2013). Cost-benefit analysis of construction information management system implementation: Case study. *Journal of Construction Engineering and Management*, 139(4), 445-455. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000611

Zhu, L., M. Shan & Z. Xu. 2019. "Critical review of building handover-related research in construction and facility management journals." *Engineering, Construction and Architectural Management.* 28 (1), 154-173. https://doi.org/10.1108/ECAM-10-2018-0442

R3ER (Resilient, Equitable, Environmental, Energy efficiency, Rapid) Shelter Design

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This research aims to provide the shelter design called R3ER (Resilient, Equitable, Environmental, Energy efficiency, Rapid) in a modularized based-3Dprinting construction method. The R3ER entails an energy-efficient design that showed a lower EUI compared to the benchmark EUI approved by ASHRAE Standards Committee. Additionally, the provided shelter R3ER has multiple uses such as disaster relief shelter, office, and hospital which can justify the environmental justice. Therefore, the R3ER will give stakeholders such as emergency planning commissions, third-party organizations, and construction managers/engineers a resource to maximize the non-monetary and monetary benefits of use of this type of shelter in their community. As a result, the communities would not only (1) be less exposed to disaster damage or less vulnerable to disaster impacts but also (2) ensure maximum utilization of the limited resources to reach out to a larger number of people who might be facing it.
Key Words: Shelter design, Jump into STEM, Energy Efficiency, Modularization, 3D printing

1. Background

There have been fifty-eight tsunamis in the past 100 years, with more than 260,000 casualties (Imamura et all 2019). Since such natural disasters would damage infrastructures, such as houses and buildings, the local people would be exposed in the probability of loss of life, injury or destruction. In addition, the lack of readily available, affordable permanent emergency housing is restricting the preparedness and function of communities worldwide, impeding many community's monetary and non-monetary attributes. Therefore, disaster relief shelters are very important in large-scale disasters and prevent communities and local peoples from the unexpected treats. The objective of this research is to proposed shelter called R3ER (Resilient, Equitable, Environmental, Energy efficiency, Rapid) based on (1) disaster resistant & multi-purpose design, (2) construction method, (3) energy efficiency, and (4) economic analysis: market readiness.. In order to design the optimized shelters, this research identified construction materials that can resist natural disasters. The R3ER has its energy consumption below the targeted energy, which suggested energy consumption of the model is below permissible limit. Therefore, the proposed shelter design provided optimized shelter designs in all aspects of building construction, structure, enclosure, and energy systems. Furthermore, it is expected that the R3ER would help stakeholders and decision makers achieve equity in environmental and energy justice and remediate social, local economic, and health burdens.

"Shelter" indicates a safe and secure place to provide food, water and health care. However, most post-disaster shelters are disposable (tents), and long-term safety is not guaranteed. This research proposes a permanent shelter design. First, this research identifies building materials and structures that have survived different types of natural disasters. Table 1 explains existing disaster resistant buildings. Alma hall, UST main building, The Sand palace were built as concrete buildings. Therefore, it is revealed that concrete, as a structural material and as the building exterior skin, has the ability to withstand nature’s normal deteriorating mechanisms as well as natural disasters.

Table 1

Disaster resistant buildings

Authors	Building name	Materials	Disaster faced	Description
(Clem, 2009)	Alma Hall	Concrete, Brick, Wood, Metal Structural Beams	Johnstown Flood (1889)	Built-in 1884, Capable of housing 246 men and women
(Santos, 2008)	UST Main Building	Concrete, Bricks, Wood, Metals, Aggregates	Earthquake (1937, 1968, 1970, & 1990)	Built-in 1927 known as first EQ- resistant building in Asia, 68502ft² and capable to withstand 9 intensity EQ
(Levenson, 2018)	The Sand Palace	Concrete, Rebar, Steel Cables	Hurricane Michael (2018)	Built-in 2017, Can withstand 240-250 mph winds
(Hi-Tech, 2016)	East Pagoda, Yakushiji Temple	Wood, Metal	Different Earthquakes	Built-in 1300 years ago and used core pillar as central column vibration control

The shelters found in Table 2 outlines the current existing emergency shelters provided around the world for refuges and disaster survivors. As shown from the Table 2, WeatherHyde was built within 15 minutes with nylon and polyester wool and Emergency SmartPod was built withing 20 minutes with aluminum panels and steel frame; these shelters are portable, fast to build, and durable. Common shapes among the designs include rectangles, pentagons, and hexagons. Some shelters can be interconnected tents or metal trailers. These shelters provide essential protection from nature while providing privacy to the outside world. Additionally, most of the examples took place in areas with high refuge or places that experience frequent natural disasters like Syria, India, and America.

Table 2

Current existing shelters

Authors	Shelter name	Material used	Cost	Construction durations	Total area
(Cooke, 2017)	WeatherHyde, 2013	Nylon, Polyester wool, Fiber reinforced mylar	$199	15Minutes	29ft²
(Better Shelter, 2021)	Better Shelter, 2015	Polyolefin panels & galvanized steel, woven high-density polyethylene fibers	$1260	4-6Hours	188ft²
(Gupta, 2012)	Hexyurt, 2011	Cloth, Wood, Plastic, Polyiso insulation, OSB, Sandwich panels, Cardboard	$229.71	4Hours	41-276 ft²
(Baylor College of Medicine, 2021)	Emergency SmartPod, 2015	Aluminum panels and steel frame	$195K - $485K	20Minutes	398ft²
(Domo, 2021)	MTS DOMO Systems, 2014	Aluminum, Polyester PVC tarpaulin, Cotton	$4625	25Minutes	252ft²

3D printing is new construction-technique which is gaining popularity in the construction sector. before it was used only for prototyping. Because of its duration of construction, capability to construct complex structures, and cost of construction, 3D printing in the construction sector has proven to be beneficial than the conventional method. Different types of materials can be used for printing structures. The structures can either be printed onsite or offsite. The structures printed offsite can be transported later to the site for installation. Among the varied materials, concrete is one of the famous materials used for printing infrastructures. Table 3 indicates representative examples of 3D Printed buildings that are found around the world. 3D printed commercial building (Dubai) is printed offsite, construction cost is $140K, and total printing durations is 17 days whereas 3D printed home (New York, US) is printed onsite, construction cost is $299.99K, and printing durations is 2 days for almost similar area. Examples in the table shows onsite printing has a less printing durations whereas offsite printing has comparatively less construction cost.

Table 3

Concrete 3D-printed building around the world

Authors	Building name	Printed onsite/offsite	Construction cost	Printing durations	Total area
(Kira, 2015)	Ten 3D Printed Houses (China)	Offsite	$4800	1Day	200ft²
(Mohan, 2020)	3D printed Commercial Building (Dubai)	Offsite	$140K	17Days	242ft²

(Carlson, 2020)	3D printed House (Belgium, China)	Onsite	-	3Weeks	90ft²
(Olick, 2021)	3D printed Home (New York, US)	Onsite	$299.99K	2Days	139ft²
(Overbeeke, 2021)	3D printed Home (Netherland)	Offsite	$946/month	2Days	94ft²
(Englefield, 2021)	East 17 Street Residencies (Austin, US)	Onsite	$450K & above	7Days/ home	90-185 ft²

2. Methodology

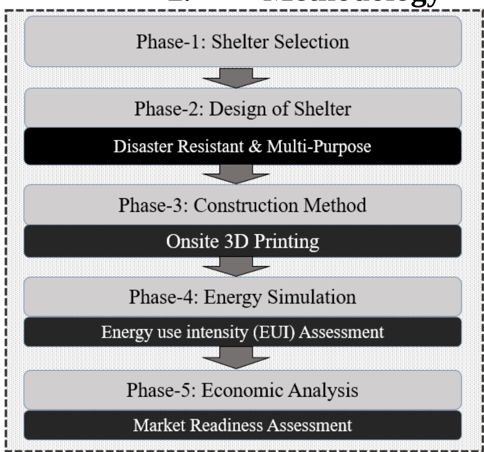


Figure 1: Research Methodology

The methodology used for the objectives set by the research can be seen in figure 1. Its framework is based on five phases: Shelter selection, Design of Shelter, Construction method, Energy simulation, and Economic analysis. The shelter selection (Phase 1) phase is related to the selection of feasible locations for the disaster relief shelter design. The criteria to select the feasible location is (1) accessibility to highway, grocery stores, and hospital, (2) accessibility to the airport, (3) plenty of open space, and (4) accessibility to the agricultural station. This phase aims to select the locations that resolve the need for shelter and alternative uses of the shelter after the disaster recovery.
The design of the shelter (Phase 2) is focused on three primary elements: disaster resistance, speed and cost of construction, and modularity. The shape of the structure is designed to be resistant to elements that could be found in a disaster scenario. This includes the exterior and interior walls utilizing design elements from the structure to be seismic, wind, and water resistant. For the construction method (Phase 3), an investigation was done for current 3D Printer Specifications. Onsite gantry printers are considered for the construction of a shelter as they have the ability to make larger prints, cost, and stability advantages compared to robotic arm printers (COBOD, 2022). The gantries inside these printers are moved by stepper motors that use digital pulses (Whiteclouds, 2021). The shelter is printed along x, y, and z coordinates with an average speed of 9.22 inches per second. The average print dimensions are 30.73’(l) x 38.64’(h) x 12.21’(w). Energy simulation (Phase 4) is conducted to determine the energy consumption of the shelter with the help of software Sketchup and Openstudio. Different building types, space types, standard templates, and climate zone are firmed on the design and location of the shelter. The energy simulation would help to determine the Energy Use Intensity (EUI). Energy Use Intensity (EUI) is the energy consumption of the building per total floor area of the building per year which is calculated in the EnergyPlus report from Openstudio software.

Then, the EUI of the shelter is compared with the benchmark EUI approved by ASHRAE Standards Committee. The EUI of shelter should be less than the benchmark EUI for energy efficiency. Considering economic analysis (Phase 5) the designed shelter is expected to substantially contribute to the local economy and business continuity by playing roles of local landmarks and reflecting the resilience of the local economy in disaster situations. The economic analysis is conducted based on the market readiness for monetary and non-monetary attributes of the shelter. This analysis for the designed shelter will not only help to save lives but also allow business continuity during the disaster when considering the economic added value and brand value.

3. Case Study

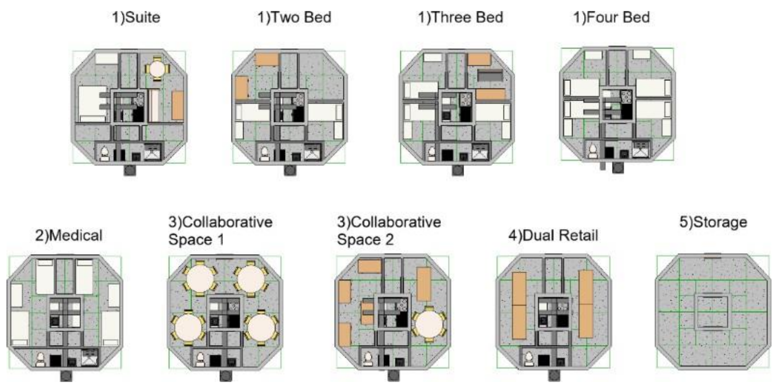
The proposed framework is applied to the shelter design in Stillwater, OK to validate the methodology process. The population of Stillwater is 50,000 people (Bestplaces, 2021), growth rate present is 28% since 2000 (Bestplaces, 2021), 1.4% average annual rate, and predicted growth rate is 29.4% (Bestplaces, 2021). This location was selected due to more diversities including residential district, local business, college town with students at Oklahoma State University. With an aim to provide environmental and energy justice-based shelter design in the form of construction method, multiple uses of the shelter design, and energy efficiency, we created a holistic real-world scenario “R3ER” ensuring the functions. The “R3ER” is designed to build using 3D Printing technique at Stillwater, OK.

Phase 1: Location of R3ER

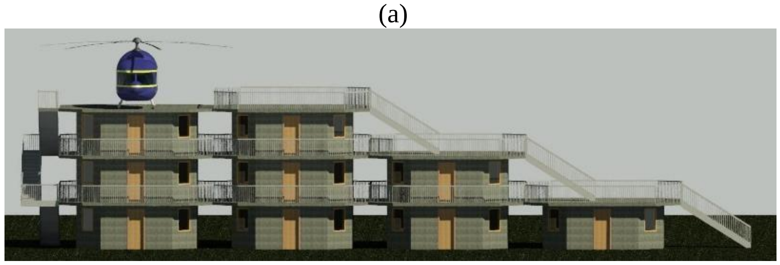
The research selected four feasible locations for the R3ER selected at Stillwater, Oklahoma for 2000 shelters. The land availability for Area 1 is 32,060,160 sf, Area 2 is 20,908,800 sf, Area 3 is 55,756,800 sf, and Area 4 is 62,726,400 sf . The scenario of a natural disaster assumes that 2000 units with 4000 residents will be found in need of shelter.

Phase 2: Design of shelter

Concrete as construction materials and octagon shapes have also been selected for optimal speed and materials usage in consideration of a 3D printer. Oklahoma is prone to earthquake as much as California due to industrial practice known as wastewater disposal (Sanburn, 2016). Regarding a disaster resistance design of the shelter unit, R3ER adopted the concrete central pillar at the core of the shelter as an East pagoda, Yakushiji Temple (Nakahara 2000). As in East pagoda, the central pillar will act as the vibration suppression (earthquake countermeasure). This vibration suppression absorbs and minimizes ground vibration (Hi-Tech, 2016). The R3ER design is capable of being stacked and the interior elements can be placed where needed to match the needed function of the structure. Figure 2 shows render images of R3ER design. Figure 1(a) reflect the modularity of a unit, which is designed to be used for multiple purposes such as commercial or residential and figure 1(b) displays the ability to stack and link shelter units based on space and desired design.



(a)



(b)

Figure 1: Renders of Design (R3ER): (a) modularity of the unit; (b) stack ability of the shelter

Phase 3: 3D printing-based construction cost

To construct 2000 shelters three printers are assumed to be used with an average printing speed of 9.22 inches per second. Table 4 displays the total construction cost for the R3ER for one unit which would be $14,349.54. The total cost includes the cost of interior walls, doors, and appliances i.e., $8840.97 along with cost of constructing the exterior walls and HVAC. The average price for a 3D concrete printer ranges from$350,000-550,000 (COBOD, 2021). Additionally, the expected duration for one unit based on the literature review would be 2 days, with the addition of cure time based on environmental conditions. The average unit cost per square foot and average durations for existing shelter printed using onsite technique is $2397.19/ft² and 18.75 days respectively with help of Table 3.

Table 4

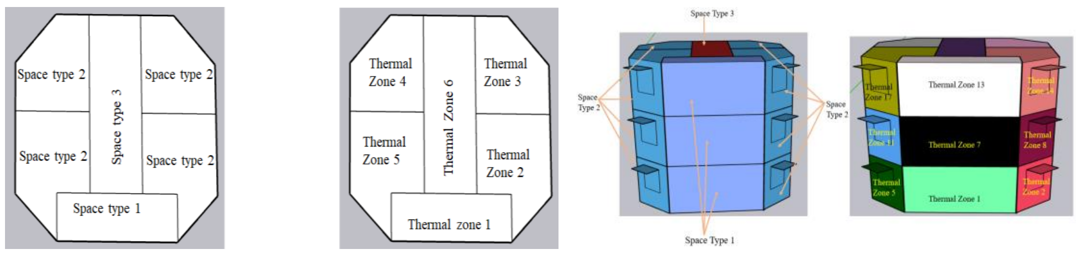
Unit cost of design (RS Means, 2021; HomeDepot PC, 2021)

Type	Count	Total
Slab	19.703 cy	$2,620.50
Structural Walls	18.913 cy	$2,515.43
HVAC	1	$1,089.00
Windows	4	$227.04
Door	1	$139.00
Labor	50 hrs.	$2,250.00
Total		$8,840.97
Optional:		
Interior Walls	310 sf	$2,170.00
Doors	4	$556.00

Appliances	7	$2,782.57
Total		$14,349.54

Phase 4: Energy simulation

Considerations are set for the simulation such as : Large Hotel building type, ANSI/ASHRAE/IES standard 90.1-2010 template, and ASHARE 169-2006-3A climate zone. Figure 2(a) shows three different space types and six thermal zones allocated to each unit whereas Figure 2(b) represents different space types which are 3 and thermal zones which is 18 for shelter when 3 units are stacked. For HVAC system Packaged Rooftop Heat Pump was used.



(a) (b)

Figure 2: Space types & Thermal Zones : (a) single unit with single floor ; (b) single unit with three floors

We took benchmark EUI of Hotel from ASHARE 169-2006-3A climate zone as shelter model is considered as large hotel building type. Table 6 illustrates EUI of Cowboy Cover and benchmark. It is observed that the energy consumption of R3ER Shelter (i.e., Site EUI 47.50 kBtu/ft² and Source EUI 150.55 kBtu/ft²) is comparatively low than the targeted energy (i.e., Site EUI 51 kBtu/ft² and Source EUI 161 kBtu/ft²) for such building type which suggested energy consumption of R3ER is below permissible limit. Therefore, the R3ER are confirmed to be energy efficient shelters provided for natural disasters relief.

Table 6

Energy Use Intensity of shelter and benchmark

	Site EUI (kBtu/ft²)	Source EUI (kBtu/ft²)	Reference
R3ER Shelter	47.50	150.55	From EnergyPlus report
Benchmark (Hotel)	51	161	(Addendum, 2017)

4. Economic Analysis: Market Readiness

Table 7 presents the markets readiness analysis of the R3ER. The R3ER provide 2000 shelter unites in the designated feasible areas. It is assumed that 50% of shelter units are kept vacant for using the space as an emergency shelter post disaster and 50% of shelter units are used for commercial purpose such as hotel, business space, hospital room, and storage unit as shown in Table 7. This 50% vacant and 50% occupied with commercial purpose would provide both monetary and non-monetary attributes to the R3ER. As per the table 7, is clear that when 1000 units are used as a hotel, office, hospital room, and storage unit in Stillwater, OK it is expected to earn S3000K/month, $624K/month, $47,910K/month, and $75K/month of financial profit respectively. Furthermore, the R3ER will not only save 4,000 lives but also allow business continuity under the disaster when considering the economic added value and brand value. Therefore, such an economic and social ripple effect will lead Stillwater to reach out twice (2.8%) higher than the current growth rate at 1.4%.

Table 7

Market readiness analysis

Assumption: 2000 units with 400 SF/unit				Occupancy: 1000 units	
Benefit	Shelter	Hotel	Business Space	Hospital room	Storage Unit
Monetary		Between $80 and $125/night (Tripadvisor, 2021)	Business space: $1.56/sf (CREXI, 2021)	$1597/ night (Hanley, 2021)	Between $50 to $100 /month (StorageArea, 2021)
(Hi-Tech, 2016)	Saved 1000 units x 4 people =4000 people	3,000,000 $/Month Attracting economic growth	624,000 $/Month Attracts new businesses	47,910,000 $/Month Adds medical location	75,000 $/Month Additional storage

5. Conclusion & Impact

R3ER the holistic solution was aimed to provide environment-friendly shelter (1) disaster resistant & multi-purpose design, (2) construction method, (3) energy efficiency, and (4) economic analysis. The literature review revealed that concrete housing has been resistant to several disasters in world history, which led us to use concrete as the construction material for the shelter. 3D printing on-site construction method is adopted as it allows faster and more accurate construction of R3ER as well as lowering labor costs and producing less waste. The central pillar at the core of the building as of East Pagoda at Yakushiji Temple (Hi-Tech, 2016) is applied to shelter design. The central pillar structure has long been thought to be the key to the pagoda's exceptional earthquake resistance. R3ER has a multi-use purpose including a shelter, hotel, office, or hospital pre or post-disaster along with disaster-resistant shelter. Additionally, the energy consumption of R3ER is calculated with help of Openstudio. The EUI of the R3ER is compared with the benchmark EUI approved by ASHRAE Standards Committee. Therefore, the R3ER could facilitate the transition from pre-disaster life to post-disaster life for people and community. As a result, the R3ER is built in locations that can be easily accessed without external help and a permanent solution to the housing demand after a disaster, and it will have a major impact on the local economic recovery.

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Reference

Addendum, A. (2017). *ANSI/ASHRAE/IES Addendum b to ANSI/ASHRAE/IES Standard 100-2015*. www.ashrae.org

Baylor College of Medicine. (2021). *Smart Pod*. https://www.bcm.edu/community/global-outreach/global-health/innovation-center/smart-pod

Better Shelter. (2021). *Where we work : Better Shelter*. https://bettershelter.org/where-we-work/

Carlson, C. (2020, December 22). *Kamp C completes two-storey house 3D-printed in one piece*. Deezen. https://www.dezeen.com/2020/12/22/kamp-c-completes-two-storey-house-3d-printed-one-piece-onsite/

Clem. (2009). *UST Main Building – Architecture Wander*. https://architecturewander.wordpress.com/2009/03/19/ust_main_building/

COBOD. (n.d.). *COBOD - Modular 3D Construction Printers - 3D Printed Buildings*. Retrieved November 10, 2021, from https://cobod.com/

Cooke, L. (2017). *Reversible weatherHYDE tent saves lives in extreme weather*. https://inhabitat.com/reversible-weatherhyde-tent-saves-lives-in-extreme-weather/

Crexi. (n.d.). *Stillwater, OK Commercial Real Estate for Lease | Crexi.com*. Retrieved November 10, 2021, from https://www.crexi.com/lease/properties/OK/Stillwater

Domo. (2021). *DOMO-System-DOMO-SYSTEM*. https://www.domo-system.org/our-story-1

Englefield, J. (2021, March 16). *3D-printed houses from disaster-proof concrete* . Dezeen. https://www.dezeen.com/2021/03/16/icon-3d-printed-houses-austin-texas/

Gupta, V. (2012). *Hexayurt Design and Construction*.

Hi-Tech. (2016). *Tokyo Skytree, Supported by 1300-year-old Technology - Hi-tech - Kids Web Japan - Web Japan*. https://web-japan.org/kidsweb/hitech/16/skytree.html

Kira. (2015). *WinSun's 3D Printed houses, Villa and Appartment*. 3ders. http://www.3ders.org/articles/20150118-winsun-builds-world-first-3d-printed-villa-and-tallest-3d-printed-building-in-china.html

Levenson, E. (2018). *This "Sand Palace" on Mexico Beach survived Hurricane Michael. That's no coincidence. | CNN*. https://www.cnn.com/2018/10/15/us/mexico-beach-house-hurricane-trnd/index.html

Mohan, R. (2020, June 21). *3D Printed Commercial Building* . The Economic Times/ Panache. https://economictimes.indiatimes.com/magazines/panache/print-to-build-worlds-first-3d-printed-commercial-building-is-here/articleshow/76490308.cms?from=mdr

Nakahara, K. O. J. I., Hisatoku, T., Nagase, T., & Takahashi, Y. (2000). Earthquake response of ancient five-story pagoda structure of Horyu-Ji temple in Japan. *Proceedings of the WCEE*.

Nembhard, H. B., Aktan, M., 2009. Real options in engineering design, operations, and management. CRC Press.

Ng, F. P., Björnsson, H. C., Chiu, S. S., 2004. Valuing a price cap contract for material procurement as a real option. Constr. Manag. Econ. 22, 141–150.

Olick, D. (2021, February 25). *3D Printed house on Sale*. CNBC Television. https://www.youtube.com/watch?v=bj8kZ3llS5E&ab_channel=CNBCTelevision

Overbeeke, V. B. (2021, April 30). *First resident of 3D-printed concrete house in Eindhoven receives key*. TU/E. https://www.tue.nl/en/our-university/departments/electrical-engineering/department/news/news-overview/30-04-2021-first-resident-of-3d-printed-concrete-house-in-eindhoven-receives-key/#top

Paddock, J. L., Siegel, D. R., Smith, J. L., 1988. Option valuation of claims on real assets: The case of offshore petroleum leases. Q. J. Econ. 103, 479–508.

Ryan Hanley. (n.d.). *How Much Does a Night in the Hospital Cost? | Trusted Choice*. November 2, 2021. Retrieved November 10, 2021, from https://www.trustedchoice.com/insurance-articles/life-health/cost-night-hospital/

Santos, T. (2008). *Is UST ready for the 'big quake'? | The Varsitarian*. https://varsitarian.net/news/20081117/is_ust_ready_for_the_big_quake

Storagearea. (n.d.). *Storage Units in Stillwater, OK - StorageArea*. Retrieved November 10, 2021, from https://www.storagearea.com/search.html?q=stillwater-ok&aid=44152-14448096-94974603&utm_source=google&utm_medium=cpc&utm_campaign=storage-unit-stillwater-ok&utm_content=&utm_term=storage unit stillwater&utm_a=&utm_t=p&utm_n=g&utm_c=42674757515&utm_p=&utm_

WhiteClouds. (n.d.). *Gantry in 3D Printers | WhiteClouds - WhiteClouds*. Retrieved November 10, 2021, from https://www.whiteclouds.com/3dpedia/gantry/

Imamura, F., Boret, S. P., Suppasri, A., & Muhari, A. (2019). Recent occurrences of serious tsunami damage and the future challenges of tsunami disaster risk reduction. Progress in Disaster Science, 1, 100009.

Reporting and Information Sharing Indicators for Positive Safety Culture in Construction Companies

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Shared values and beliefs are inherent in a culture, which helps an organization achieve superior safety performance. The study aimed to identify the reporting and information-sharing indicators that will promote positive safety culture within construction companies, especially among small and medium-sized enterprises (SMEs). Based on the related literature on safety culture, the study adopted the Delphi technique data collection method in Ghana, the research site. After a three-round Delphi technique, the indicators that reached consensus were retained and reported in this paper. The findings revealed that 11 indicators would show how reporting and information sharing promote a positive safety culture. Reporting and sharing information underpin an informed culture essential to a learning organization. Thus, how construction SMEs handle specific indicators, such as 'naming and shaming [the blame game], influence the timing and accuracy of reporting and sharing of information that may be vital to the safety of site operatives.

Keywords: Construction, Contractors, Safety Culture, Safety Information.

Introduction

The construction industry is considered one of the most dangerous due to its high rates of injuries, accidents, and fatalities. The impact of construction site accidents is high since it accounts for substantial workplace accidents (Mohammadi et al., 2018). Umeokafor et al. (2022) pointed out that the accident rate within African countries is 21.1 fatalities per every 100,000 workers. In South Africa, for example, there is a positive relationship between lost days and the average cost per accident, which means that for every increase in lost days, there is a corresponding increase in the cost of accidents (CoA) (Aiyetan & Anugwo, 2021). According to Bavafa et al. (2018), the case in Ghana is a concern. The available worker's compensation report confirmed that from 2010 to 2016, over 558 accidents occurred on construction sites in Kumasi and Accra (Simpson & Sam, 2019). The poor H&S performance of construction SMEs has been attributed to several factors, such as a lack of safety culture within construction SMEs regarding self-protection and awareness, ineffective H&S legislation and regulations, poor communication of safety programs, construction SMEs ignoring safety due to time pressure of the project schedule, poor personal attitudes toward H&S and lack of enforcement of safety compliance (Agyekum et al., 2018). There is, therefore, the need for construction SMEs to address this negative safety performance to remain competitive.

To curtail the high accident rates in construction SMEs, there has been a considerable increase in the call to focus on proper management of H&S of construction workers across the globe. Construction SMEs continue to engage in unsafe acts and conditions because of an absence of a positive safety culture. Construction SMEs must formulate adequate measures and approaches that will lead to safety behavior, hence safety compliance on construction sites. These approaches should focus on the work environment and frontline operatives' beliefs, attitudes, and behaviors (Ardeshir & Mohajeri, 2018). This has led to introducing a safety culture to always commit workers to their safety and that of their co-workers during and after work. Positive safety culture paves the way for a safer workplace through improvements in technology, work design changes, personal protective equipment (PPEs), and modifications in construction performance (Hofmann et al., 2017). However, the literature is silent on the role of safety reporting and information concerning how to engender a positive safety culture. The limited literature on the subject informs the reported study in this paper. The study aimed to identify the key indicators of safety reporting and information sharing that will promote positive safety culture within construction SMEs. As such, the paper presents the indicators of safety reporting and information sharing that should promote positive safety culture within construction SMEs, using Ghana as a case in point. The indicators highlighted in the paper apply to construction SMEs in developing and developed countries.

Literature Review

Positive Safety Culture

Safety culture is the set of enduring values and attitudes regarding safety issues; shared by every member at every level of an organization. It comprises shared values and beliefs in an organization (Miang, 2018). It refers to the extent to which every individual and every group of the organization is aware of the risks and hazards induced by its activities; is continuously behaving to preserve and enhance safety; is willing and able to adapt itself when facing safety issues; is ready to communicate safety issues and consistently evaluates safety-related behavior (Piers et al., 2009). Aburumman et al. (2019) believe that poor safety culture within an organization creates an environment for errors and violations of safety rules and practices, which leads to increased accidents. It also exposes management's inability to acknowledge or address safety-related issues within the organization.In contrast, positive safety culture is the engine that drives the system towards the goal of sustaining the maximum resistance towards its operational hazards (Aburumman et al., 2019). Positive safety culture is an informed culture that improves company safety performance (Miang, 2018). A critical element of a positive safety culture is the reporting and sharing of safety information, succinctly highlighted in the next section.

Safety Information

Safety information echoes the extent to which it is disseminated among employees of an organization at the right time and with the right people (Piers et al., 2009). Construction SMEs must be encouraged to communicate safety-related information in the right way, at the right time, and in the p manner to the right people at construction sites to avoid hazardous situations that will lead to injuries, accidents, and fatalities. For any safety management system to be successful, safety information must be communicated throughout the construction firm because effective communication provides a robust safety management system. Piers et al. (2009) reported that sharing safety information properly is needed to develop an understanding of the different types of hazards and risks on construction sites, ensure that assigned roles and responsibilities to employees are well understood, and identify exposures and determine the level of risk and develop appropriate mitigations against dangers. Safety information is crucial in planning safety to recognize hazardous situations at construction sites. It helps analyze health and safety status at any stage of the construction process, as it underpins the identification of the root causes of injuries, accidents, and fatalities at construction sites (Manase et al., 2011). According to Eyiah et al. (2019), poor implementation of safety information within construction SMEs will negatively impact employees, employers, progress, productivity, and profit margins, resulting in more injuries, accidents, and fatalities in construction operations. The safety information communicated and received by construction SME workers must be accurate, correctly recognized, and easily interpreted to establish a positive safety culture.

When a safety culture is considered, Chen et al. (2021) says that information sharing bridges workers' behavior with expected safety outcomes. Safety information sharing contains information that most often indicates the safety status of a particular activity from employer to employees within an organization (Luo & Wu, 2019). It is, therefore, appropriate to assume that incidents, near misses or accidents, may occur when there is a failure in safety information sharing. For instance, injuries, accidents, and fatalities are related to wrong safety information supply, incorrect safety information cognition, and faulty safety information feedback (Wu & Huang, 2019; Chen et al., 2021). For any safety system to be successful, safety information must be timely, accurate and well-understood by relevant parties to avoid accidents. Wu and Huang (2019) iterated that possible breakdowns in safety information sharing can be analyzed from failures of the acquisition of safety information, failures of the analysis of safety information and failures of the utilization of safety information.

Research Method

According to Piers et al. (2009), safety culture can be assessed through qualitative and quantitative means. They added that a researcher could use questionnaires or interviews during the assessment process. The Delphi method was selected and expedited in this study with a list of H&S experts identified from Ghana. The Delphi survey is preferred by scholars who aim to obtain a consensus among specialists regarding a complex problem (Ameyaw et al., 2016). The selection of experts was based on country residence, knowledge of H&S, academic qualification, work experience, employment, influence and recognition, and safety association affiliation, to mention a few. The minimum selection criteria follow other scholars (Keeney et al., 2001ab; Manase et al., 2011). The Delphi survey instrument was compiled based on a review of the related literature. From the literature, 11 indicators were identified and grouped under-reporting and information sharing. Six indicators were selected for reporting (Table 1), and five were for information sharing (Table 2). Thus, these 11 indicators form the basis of the results presented in the next section of the paper.

Table 1: *Reporting indicators and measuring metrics*

Measuring metrics	**Sources**
The blame game does not hinder incident reports.	Vecchio-Sadus & Griffiths (2004)
Reporting lines and systems are clear.	Choudhry et al. (2009)
Reports lead to reviews and improvements.	Díaz-Cabrera et al. (2007)
Incident reporting is nurtured and rewarded.	Choudhry et al. (2009)
Incident reporting leads to better SWPs.	Díaz-Cabrera et al. (2007)
Workers are willing to report incidents.	Cui et al. (2013); Håvold & Nesset (2009)

Additional sources: Al-Bayati (2021) and Oswald et al. (2018)

The Delphi survey instrument requested the panel to rate the importance of the indicators in establishing a positive safety culture in construction companies using a 10-point Likert-type scale. On the scale, 1 and 2 = unimportant, 3 and 4 = slightly important, 5 and 6 = neutral, 7 and 8 = important, and 9 and 10 = very important. Since several scholars in the Delphi survey literature observed that the most accurate results of the Delphi process were obtained after two iterations, the survey for this study was terminated after three rounds. The outcome of the 3rd round is presented in this paper. While recognizing other views on the agreement within a Delphi survey panel, the median and percentage were used to determine consensus in the current study. A consensus was reached when each indicator attracted a final median score of 'importance' of 5-10, and more than 50% of the experts rated each indicator between 5 and 10. Notably, the 11 indicators presented in this paper attained consensus among the panel.

Table 2 *Information sharing indicators and measuring metrics*

Measuring metrics	**Sources**
Safety information is in multiple languages.	Vecchio-Sadus & Griffiths (2004)
Voluntary safety information-sharing exists.	Milijic et al. (2013)
New safety regulations are shared timely.	Bronkhorst et al. (2018)
Safety concerns receive timely attention.	Bronkhorst et al. (2018)
SWP information is shared timely.	Petschonek et al. (2013)

Additional sources: Nitsche (2019), Zou et al. (2017)

After the selection, 31 experts were approached, but only 18 participated in the study. This confirmed the argument made by Trevelyan and Robinson (2015) and Keeney et al. (2001) that as the number of Delphi rounds increases, the more likely it is for participants to begin to drop out of the successive rounds due to either fatigue, attrition rates, time, or cost. Despite the attrition rate, the participants in the Delphi survey cut across the major cities in Ghana. In selecting the panel of experts, a balance between those in the academia and practitioners was sought to reduce bias. The experts were made up of 14 men and four women. Six per cent of them held professorial degrees, 33% had a doctoral degree, 55% held master's degrees, and 6% failed to indicate their academic qualifications. Of the 18 respondents, nine were academicians lecturing at leading universities in Ghana, while others were professionals in the construction safety space.

Data Analysis and Results

As shown in Table 3, reporting had six indicator metrics that measured it. All the six-indicator metrics were rated very high, with minimum median importance of 7 and a response percentage higher than 80%. All six have achieved the required consensus and retained. This is in line with the results in rounds 1 and round 2. More than 50% of the experts rated all six indicators as important to significantly impact positive safety culture for improved construction SMEs safety performance. The data suggest that the leading indicator metrics impact positive safety culture among construction SMEs. The Delphi survey experts with cognate exposure to H&S matters agreed that all six-indicator metrics measuring safety reporting are critical in positively influencing safety information in establishing positive safety culture among construction SMEs. In addition, information sharing was measured with five indicator metrics. The indicators attained the critical consensus and were retained. This is in line with the results in rounds 1 and round 2. More than 50% of the experts rated all five indicators as essential to significantly impact positive safety culture for improved SME safety performance. The table also shows that the Delphi survey respondents agreed that five indicator metrics would positively impact safety information sharing among construction SMEs that will promote positive construction safety culture. The results implied that no reporting and sharing of safety information among construction SMEs in Ghana would promote a positive safety culture.

Table 3 *Important leading indicators of reporting and information sharing*

S/N	Positive construction safety culture core elements and their leading indicator metrics	% Response (5-10)	Importance Mean	Importance Median
	Reporting			
1.1	Blame game hinders incident reports	93.80	7.90	8.00
1.2	Reporting lines and systems are clear	93.80	7.60	8.00
1.3	Reports lead to reviews and improvements	93.80	7.40	8.00
1.4	Incident reporting is nurtured and rewarded	81.30	7.40	7.00
1.5	Incident reporting leads to better SWPs	87.50	7.60	8.00
1.6	Workers are willing to report incidents	87.50	7.60	8.00
	Information-sharing			
2.1	SWP information is shared timely	75.00	7.20	8.00
2.2	Safety information is in multiple languages	75.00	6.70	7.50
2.3	Voluntary safety information sharing exists	75.00	6.50	7.50
2.4	New safety regulations are shared timely	75.00	7.20	8.00
2.5	Safety concerns receive timely attention	81.30	7.60	8.50

Discussion

Safety climate can be used to assess and improve site safety for projects under construction (Choudhry et al., 2007). Similarly, safety information is critical in establishing positive construction safety culture among construction SMEs (Biggs et al., 2013; Gunduz & Laitinen, 2017; Piers et al., 2009). For this current study, two core elements of safety culture were highlighted: safety reporting (Al-Bayati, 2021; Oswald et al., 2018) and safety information sharing (Nitsche, 2019; Pedro et al., 2022; Zou et al., 2017). The two core elements (reporting and information sharing) were essential in influencing safety culture. Eleven leading indicator metrics (six measured reporting and five measured information sharing) were agreed upon by the H&S experts to significantly impact safety information for improved positive construction safety culture among construction SMEs in Ghana. The six reporting indicators received a higher median score of 7-8, confirming the opinions and judgements of the experts that if accidents and near misses were reported early and actions were taken at the right time, this would lead to considerable reductions in accidents in construction sites. There should be a robust accident reporting system to eliminate the “fear of blame” for improving safety culture in construction companies, as illustrated in Langer (2021). This indicates that when construction workers are aware of their responsibilities to report injuries, accidents and fatalities on construction sites, their motivated to keep the areas safe for solid safety culture. Williams et al. (2020) supported these results by stating that when there are no concerns about why accidents occur on construction sites and why these accidents are not reported, it prevents how accidents must be stopped, which is a sign of negative safety culture. Ensuring a proper accident reporting norm is necessary to eliminate injuries, accidents and fatalities (Boadu et al., 2021).

In addition, the results indicated that a lack of safety information flow among construction SMEs should be a concern. This concurred with Gyensare et al. (2019). They reported that the high rates of accidents among construction SMEs in Ghana are due to a lack of appropriate flow of safety information among the employees of relevant firms. Eyiah et al. (2019) mentioned that the inability of construction SMEs to implement proper safety information flow would negatively impact employees, employers, the progress of work, productivity, profit margins and H&S performance. They claimed these are the major causes of injuries, accidents, and fatalities in the construction industry. The negative impact of safety information on safety culture means some construction firms may not consider safety information as the bridge connecting workers' behavior, as indicated by Chen et al. (2021).Previous research contends that when construction SME employees have greater access to suitable H&S information-sharing systems, positive safety culture would be firmly upheld in these construction firms. Yorio et al. (2019) advocated that whenever there is a lack of sharing safety information among construction workers, they would have low interest in safety culture programmes. All five indicators measuring information-sharing attained consensus and were retained. Over 75% of the experts acknowledged that these indicators are fundamental, with median values between 7 and 8. This affirmed the experts' opinions that, if information sharing were well addressed, it would promote a positive safety culture within the construction industry. This result is also in line with the results of the Delphi survey round 1 and round 2.

Conclusion

Reason's model of safety culture (1997) highlights the importance of an informed culture in a company. According to him, reporting culture, just culture, flexible culture, and learning culture make up an informed culture, which is socially engineering in an enterprise. An informed culture is a positive culture where "…in which those who manage and operate the system have current knowledge about the human, technical, organizational and environmental factors that determine the safety of the system as a whole" (Miang, 2018). To have an informed culture in construction SMEs, one must look at specific indicators. The 11 indicators outlined and discussed in this paper may be a starting point for companies, especially in the SME category.

Reporting and information-sharing indicators would help construction SMEs gather the right kind of data (leading indicators) to help them manage H&S proactively instead of relying on lagging indicators. The importance of the indicators in Table 3 from the perspective of the Delphi survey panel requires construction SMEs to design safety reporting and information-sharing systems that emphasize positive events to facilitate the character of a learning organization. It is argued that focusing on positivity helps to normalize the practice of reporting and sharing safety-related information. On the one hand, reporting and sharing information would encourage feedback that enhances compliance and behavior-based safety in construction SMEs. On the other hand, a blame and fear culture on a construction site or inside a construction SME would marginalize reporting and information-sharing to the detriment of safety. Like other methods, the Delphi survey limits generalization to a large population. Therefore, all the indicators that attained consensus in the soon-to-be-completed doctoral study were used to compile a structured questionnaire distributed to more than 400 professionals in Ghana. The general survey is further to confirm the views of the Delphi survey panel and evaluate relevant hypotheses such as:

- *H1:* Reporting positively influences the safety culture of SME construction companies

- *H2:* Information-sharing positively influences the safety culture of SME construction companies

After analysis, the general survey results will be shared with the construction management research community.

References

Aburumman, M., Newnam, S., & Fildes, B. (2019). Evaluating the effectiveness of workplace interventions in improving safety culture: A systematic review. Safety Science, 115, 376–392. https://doi.org/10.1016/j.ssci.2019.02.027

Agyekum, K., Simons, B. and Botchway, S. (2018), "Factors influencing the performance of safety programmes in the Ghanaian construction industry", Acta Structilia, Vol. 25 No. 2, pp. 39-68, DOI: 10.18820/24150487/as25i2.2.

Aiyetan, A.O. & Anugwo, I.C. (2021). Machine accidents and project delivery in Kwazulu-Natal construction industry. *Journal of Natural and Applied Sciences*, 5(1), 1-15.

DOI:10.53974/unza.jonas.5.1. Article No. 710

Al-Bayati, A. J. (2021). Impact of Construction Safety Culture and Construction Safety Climate on Safety Behavior and Safety Motivation. Safety, 7(2), 41. https://doi.org/10.3390/safety7020041

Ameyaw, E. E., Hu, Y., Shan, M., Chan, A. P. C., & Le, Y. (2016). Application of Delphi method in construction engineering and management research: a quantitative perspective. Journal of Civil Engineering and Management, 22(8), 991–1000. https://doi.org/10.3846/13923730.2014.945953

Ardeshir, A., & Mohajeri, M. (2018). Assessment of safety culture among job positions in high-rise construction: A hybrid fuzzy multi-criteria decision-making (FMCDM) approach. International Journal of Injury Control and Safety Promotion, 25(2), 195–206. https://doi.org/10.1080/17457300.2017.1416483

Bavafa, A., Mahdiyar, A., & Marsono, A. K. (2018). Identifying and assessing the critical factors for effectively implementing safety programs in construction projects. Safety Science, 106, 47–56. https://doi.org/10.1016/j.ssci.2018.02.025

Boadu, E. F., Wang, C. C., & Sunindijo, R. Y. (2021). Challenges for Occupational Health and Safety Enforcement in the Construction Industry in Ghana. *Construction Economics and Building*, *21*(1). https://doi.org/10.5130/AJCEB.v21i1.7482

Bronkhorst, B., Tummers, L., & Steijn, B. (2018). Improving safety climate and behavior through a multifaceted intervention: Results from a field experiment. Safety Science, 103, 293–304. https://doi.org/10.1016/j.ssci.2017.12.009

Chen, Y., Feng, W., Jiang, Z., Duan, L., & Cheng, S. (2021). An accident causation model based on safety information cognition and its application. Reliability Engineering & System Safety, 207, 107363. https://doi.org/10.1016/j.ress.2020.107363

Choudhry, R.M., Fang, D. Lew, J.J., & Jenkins, J.L. (2007). Assessing Safety Climate in Construction: A Case Study in Hong Kong. International Proceedings of the 43rd Annual Associated Schools of Construction Conference, 12-14 April 2007, Northern Arizona University, Flagstaff, Arizona.

Choudhry, R., Fang, D., & Lingard, H. (2009). Measuring Safety Climate of a Construction Company. Journal of Construction Engineering and Management-Asce - J CONSTR ENG MANAGE-ASCE, 135. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000063

Cui, L., Fan, D., Fu, G., & Zhu, C. J. (2013). An integrative model of organizational safety behavior. Journal of Safety Research, 45, 37–46.

Díaz-Cabrera, D., Hernández-Fernaud, E., & Isla-Díaz, R. (2007). An evaluation of a new instrument to measure organisational safety culture values and practices. Accident Analysis & Prevention, 39(6), 1202–1211.

Eyiah, A. K., Kheni, N. A., & Quartey, P. D. (2019). An Assessment of Occupational Health and Safety Regulations in Ghana: A Study of the Construction Industry. Journal of Building Construction and Planning Research, 07(02), 11–31. https://doi.org/10.4236/jbcpr.2019.72002
Gunduz, M., & Laitinen, H. (2017). A 10-step safety management framework for construction small and medium-sized enterprises. International Journal of Occupational Safety and Ergonomics, 23(3), 353–359. https://doi.org/10.1080/10803548.2016.1200258
Gyensare, M. A., Anku-Tsede, O., Boakye, K. O., & Twumasi, E. (2019). Occupational Health and Safety and Employee Engagement: Evidence from the SMEs Sector in Ghana. In P. M. F. M. Arezes (Ed.), Advances in Safety Management and Human Factors (Vol. 791, pp. 202–216). Springer International Publishing. https://doi.org/10.1007/978-3-319-94589-7_21
Håvold, J. I., & Nesset, E. (2009). From safety culture to safety orientation: Validation and simplification of a safety orientation scale using a sample of seafarers working for Norwegian ship owners. Safety Science, 47(3), 305–326.
Hofmann, D. A., Burke, M. J., & Zohar, D. (2017). 100 years of occupational safety research: From basic protections and work analysis to a multilevel view of workplace safety and risk. Journal of Applied Psychology, 102(3), 375–388. https://doi.org/10.1037/apl0000114
Keeney, S., Hasson, F., & McKenna, H. P. (2001a). A critical review of the Delphi technique as a research methodology for nursing. International Journal of Nursing Studies, 38(2), 195–200.
Keeney, S., Hasson, F., & McKenna, H. P. (2001b). A critical review of the Delphi technique as a research methodology for nursing. International Journal of Nursing Studies, 38(2), 195–200. https://doi.org/10.1016/S0020-7489(00)00044-4
Langer, C. (2021) Mindful safety: a multi-level approach to improving safety culture and performance. Boca Raton: CRC Press.
Luo, T., & Wu, C. (2019). Safety information cognition: A new methodology of safety science in urgent need to be established. Journal of Cleaner Production, 209, 1182–1194. https://doi.org/10.1016/j.jclepro.2018.10.311
Manase, D., Heesom, D., & Oloke, D. (2011). A GIS analytical approach for exploiting construction health and safety information. Ourna l of Information Technology in Construction (ITcon), 16, 335–356.
Miang, G.Y. (2018) Introduction to workplace safety and health management: a systems thinking approach. Singapore: World Scientific.
Milijic, N., Mihajlovic, I., Strbac, N., & Zivkovic, Z. (2013). Developing a Questionnaire for Measuring Safety Climate in the Workplace in Serbia. International Journal of Occupational Safety and Ergonomics, 19(4), 631–645. https://doi.org/10.1080/10803548.2013.11077020
Mohammadi, A., Tavakolan, M., & Khosravi, Y. (2018). Factors influencing safety performance on construction projects: A review. Safety Science, 109, 382–397. https://doi.org/10.1016/j.ssci.2018.06.017
Nitsche, C. I. (2019). Promoting safety culture: An overview of collaborative chemical safety information initiatives. Journal of Chemical Health & Safety, 26(3), 27–30. https://doi.org/10.1016/j.jchas.2018.12.004
Oswald, D., Sherratt, F., & Smith, S. (2018). Problems with safety observation reporting: A construction industry case study. Safety Science, 107, 35–45. https://doi.org/10.1016/j.ssci.2018.04.004
Petschonek, S., Burlison, J., Cross, C., Laver, J., Landis, R. S., & Hoffman, J. M. (2013). Development of the Just Culture Assessment Tool: Measuring the Perceptions of Health-Care Professionals in Hospitals. 9(4), 8.
Piers, M., Montijn, C., & Balk, A. (2009). Safety Management System and Safety Culture Working Group.pdf. ECAST European strategic initiative.

Simpson, K. B., & Sam, A. (2019). Strategies for health and safety management in Ghana. Journal of Engineering, Design and Technology, 18(2), 431–450. https://doi.org/10.1108/JEDT-07-2019-0189
Trevelyan, E. G., & Robinson, P. N. (2015). Delphi methodology in health research: How to do it? European Journal of Integrative Medicine, 7(4), 423–428. https://doi.org/10.1016/j.eujim.2015.07.002
Umeokafor, N., Umar, T., & Evangelinos, K. (2022). Bibliometric and scientometric analysis-based review of construction safety and health research in developing countries from 1990 to 2021. *Safety science*, 156, 105897. https://doi.org/10.1016/j.ssci.2022.105897
Vecchio-Sadus, A. M., & Griffiths, S. (2004). Marketing strategies for enhancing safety culture. Safety Science, 42(7), 601–619. https://doi.org/10.1016/j.ssci.2003.11.001
Williams, J., Fugar, F., & Adinyira, E. (2020). Assessment of health and safety culture maturity in the construction industry in developing economies: A case of Ghanaian construction industry. *Journal of Engineering, Design and Technology*, *18*(4), 865–881. https://doi.org/10.1108/JEDT-06-2019-0151
Wu, C., & Huang, L. (2019). A new accident causation model based on information flow and its application in Tianjin Port fire and explosion accident. Reliability Engineering & System Safety, 182, 73–85. https://doi.org/10.1016/j.ress.2018.10.009
Yorio, P. L., Edwards, J., & Hoeneveld, D. (2019). Safety culture across cultures. *Safety Science*, *120*, 402–410. https://doi.org/10.1016/j.ssci.2019.07.021
Zou, P. X. W., Lun, P., Cipolla, D., & Mohamed, S. (2017). Cloud-based safety information and communication system in infrastructure construction. Safety Science, 98, 50–69. https://doi.org/10.1016/j.ssci.2017.05.006

Covid-19 Impact on Faculty Research Productivity

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The response of academic institutions to Covid-19 impacted faculty in numerous ways including teaching, service, and research productivity. Thus, this research seeks to determine the United States (US). Construction faculty perceptions of Covid-19 impacts to their research. This research targeted group was US academic institutions members of the Associated Schools of Construction (ASC) grouped according to their Carnegie Institutional Classification. It was hypothesized that research of faculty in doctoral universities with very high research activity (R1) according to the Carnegie Classification would be more broadly impacted. To evaluate this hypothesis, a non-experimental correlational research approach was implemented using an online survey instrument to collect data. The data collected correspond to 109 construction educators within the US. The elements considered to impact faculty research in this study include: average teaching load, online learning environment (OLE) impact on research and service, factors affecting research productivity, overall institutional support and support to OLE. Based on the data analysis, it was determined that differences in the institutions' Carnegie Classification does not have an effect on the faculty perceptions of Covid-19 impacts, as faculty from all types of classifications indicated comparable impacts on research, service and teaching.

Key Words: Covid-19 Construction Education, Covid-19 Construction Research

Introduction and Background

The United States (US) Centers for Disease Control (CDC) provided recommended guidelines to mitigate the risk of transmitting Covid-19 including hygiene, social distancing, and others (CDC, 2020). To mitigate the risk of transmitting Covid -19, higher education systems globally followed the CDC recommendation and transitioned to electronic or Online Learning Environment (OLE) (Munoz-Najar et al., 2022). In the US, this transition occurred in March or April 2020 (Langar et al., 2022a).

Pre-pandemic researchers described how online construction education can be delivered effectively and successfully (Ahmed et al., 2016; Kelting et al., 2016). Some construction programs were already delivering construction courses via OLE. Existing research indicates a significant proportion of construction educators had limited experience with online content delivery pre-Covid (Langar et al., 2022a). Furthermore, OLE delivery has also shown to present more challenges to academic integrity (Tabas et al., 2012). OLE is particularly challenging for construction education, because courses are typically delivered via experimental laboratory exercises, hands-on experiments, project-based courses, and computer labs. These types of courses are considered more challenging to deliver with OLE versus face-to-face delivery (Adhikari et al., 2021a). Faculty may expect to invest more time in OLE content delivery (Alungbe et al., 2010; Shea et al., 2005) than face-to-face teaching (Schmidt et al., 2013). In addition to the time to development and delivery content, other factors can impact faculty such as: administrative support, (Han et al., 2018), previous experience with an OLE (Clemson et al., 2022), organizational, technological, social, and personal factors (Iwu et al., 2022). Online construction is also challenging to students. Student perceive online education to require additional time and reduce interaction with faculty and peer students (Kinney et al., 2012).

Prior research has identified the research impacts of OLE transition on educator productivity. For example, Clemson et al. (2022) identified research productivity as impacted among the pharmacy faculty in research-intensive colleges. Langar et al. (2021) studied the impact of OLE on construction educators and found improvements in teaching with OLE while a declining in overall productivity. The most common concerns impacting faculty during Covid-19 Pandemic included 1) limited interaction with the students, 2) background noise while participating in virtual meetings, 3) internet issues, 4) too many conference calls, 5) virtual meetings, and 6) limited work and life separation (Langar et al., 2022b). Further, Langar et al. (2021) found that tenured or tenure-track educators were spending less time on research, whereas “non-tenured” spent more time developing and delivering content, resulting in a productivity decline in both research and content delivery. While some research indicates the benefits of working from home (especially during the pandemic), the consensus is that a significant proportion of educators realize research productivity being impacted (Clemson et al., 2022; Iwu et. al., 2022; UCLA 2021; Langar et al. 2021).

At the time of this writing, there were one hundred forty-two 4-year construction programs and nine 2-year construction programs who were members of the Associated Schools of Construction (ASC) (ASC 2022a). However, as schools choose to self-select into or out of membership, the total membership varies. The ASC includes seven regions within the United States and Canada and one international region (ASC 2022b).

1. *Northeast: Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont, West Virginia*
2. *Southeast: Alabama, Florida, Georgia, Mississippi, North Carolina, South Carolina, Tennessee. Virginia*
3. *Great Lakes: Illinois, Indiana, Kentucky, Michigan, Ohio, Wisconsin*
4. *North Central: Iowa, Kansas, Minnesota, Missouri, Nebraska, North Dakota, South Dakota*
5. *South Central: Arkansas, Louisiana, Oklahoma, Texas*
6. *Rocky Mountain: Alaska, Arizona, Colorado, Idaho, Montana Nevada, New Mexico, Utah, Wyoming*
7. *Far West: California, Hawaii, Oregon, Washington*
8. *International (not included in this study): Asia, Australia, Canada, England, Europe*

This paper focuses on US institutions members of the ASC ranked through the Carnegie Classification of Institutions of Higher Education, indicating the level of research and the highest level of degree attainment, either Baccalaureate, Master, or Doctoral degrees (2022). Four-year Construction degrees may be in Engineering, Engineering Technology, or Construction Management programs. Within those programs, Baccalaureate, Master, or Doctoral degrees may be available. This research determines US Construction faculty perceptions of Covid-19 based on their Institution Carnegie Classification for research.

Methodology

The study used an online survey method to collect data using Qualtrics. A survey was selected for its ability to identify trends among the educators with regard to the OLE transition (Gable 1994). It was determined to conduct the survey online as most of the US population has access to the internet (Sheehan 2001) and online method provided the best value especially during the Covid-19 pandemic. All email information about the construction educators was collected online from publicly available information sets and email listservs such as the Associated Schools of Construction and the American Society of Engineering Education. The developed online instrument had various question types which included; multiple-choice, Likert scale, and both short and long essay-type questions. The survey instrument was validated for reliability and grammatical errors through pilot testing and the pilot tested instrument was emailed in the summer of 2020. Educators were also sent reminders and the survey was closed in about two months after its launch.

The overall survey was distributed to 1,883 Architecture, Engineering and Construction (AEC) faculty members via email. However, this study has a more narrow focus limiting it to construction educators only. The parameter used to identify construction educators was their self-identification as teaching construction course work or teaching in a construction program, department, or college.

Results

The study received 179 complete responses from (AEC) educators. To answer the research question, the first set of filters included affiliation with construction programs, which include Engineering, Engineering Technology, and Construction Management. After the application of this filter, the N was reduced to 121. Another set of filters, i.e., availability of university name (institutional affiliation) was applied which brough the final respondent number to 109. Out of 109 respondents, 103 respondents were identified to be affiliated with institutions that were ASC members and the remainder were from non-ASC Schools.

The number of ASC member institutions, the number of institutions represented by responded and the number of individual respondents can be seen in Figure 1 (organized by the ASC regions). There were some ASC regions which had a greater number of individual respondents. This might be attributed in part to the fact that those regions have some programs with a large number of faculty members and that the authors represent schools from Region 2 and Region 5 (which might increase the likelihood of their colleagues to response to the survey). The individual respondents were then grouped by their institutional affiliation (focus of this research). This grouping is also delineated in figure 1, where respondents are identified by member schools, based on institutional respondents (number of institutions responding), and individual respondents. It is evident when comparing institutional respondents and individual respondents that there are multiple respondents from individual institutions (figure 1).

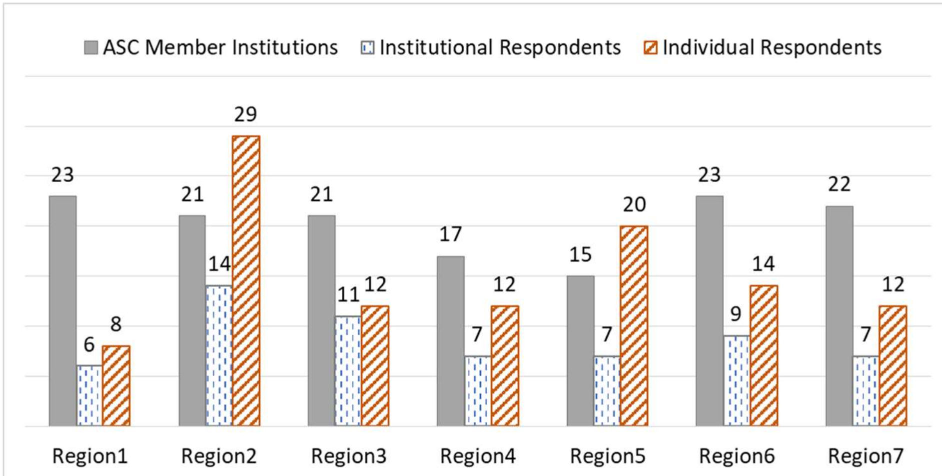

Figure 1: Distribution of US ASC Member School Respondents by Region

When considering relationships to research, thirty-seven (33.9%) respondents from land grant universities and seventy-two (66.1%) respondents represent non-land grant institutions. To further identify research requirements, the Carnegie Classification of universities was used. Of the respondents, fifty-five (50.5%) respondents were affiliated with doctoral universities with very high research activity (R1 institutions), twenty-three (21.1%) with doctoral universities with high research activity (R2 institutions), and the remaining thirty-one (28.4%) work for unclassified institutions. Respondents were asked to "select the areas that have been impacted by the transition to the online learning environment," and the options for research and service were given. Respondents could select more than one response or leave it blank. Thirty-eight (34.9%) respondents identified "research" as impacted, while forty-two (38.5%) identified "service." Overall, fifty-eight (53.2%) respondents identified research and/or service as impacted (figure 2).

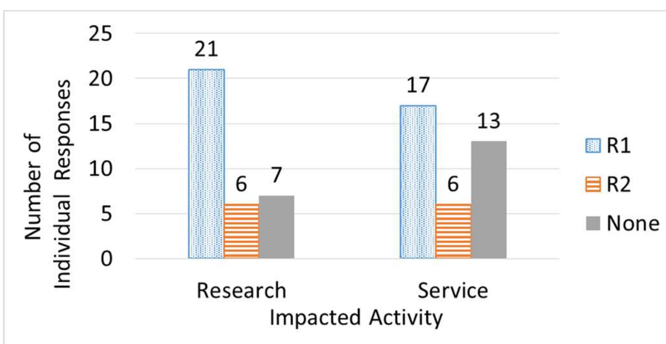

Figure 2: Respondent identifying Research/Service impacts by the transition to OLE

When considering the Carnegie Classification, twenty-one respondents from R1 institutions, six respondents from R2 institutions, and seven from non-classified institutions identified research was impacted. Similarly, seventeen respondents from R1 institutions, six from R2 institutions, and thirteen from non-classified institutions identified service was impacted. It is somewhat expected that a larger percentage of respondents from R1 institutions had impacts on research (38%), than those from R2 (26%), or non-classified institutions (23%). Conversely, it would be expected that there would be a more significant percentage of those from non-classified institutions who had service impacted (42%), versus those from R1 institutions (31%) (figure 2).

Teaching Load

When considering the annual average amount of teaching (in credit hours) by Carnegie Classification, respondents from institutions classified as R1 (53) have an average annual teaching load of 13.0 semester credit hours with a standard deviation of 5.6, with a minimum load of 2 and maximum load of 30. While respondents from R2 institutions (23) have an average annual teaching load of 15.9 semester hours with a standard deviation of 6.4, with a minimum load of 3 and a maximum load of 30. Lastly, respondents from institutions not classified (31) have an average annual teaching load in semester credit hours of 15.1 hours with a standard deviation of 6.89, with a minimum teaching load of 3 and a maximum of 27 hours annually. Two respondents from R1 institutions left this value blank and were not included in the percentage calculation. While two respondents from R1 institutions indicated they were adjuncts working part-time or three hours annually, if these faculty are removed, the change is minimal. Similarly, we could consider those teaching ten or more hours per year with R1: 37 of 51 (72.5%). It is evident that a majority of the construction faculty respondents across classifications teach 12 or more credit hours per year (figure 3).

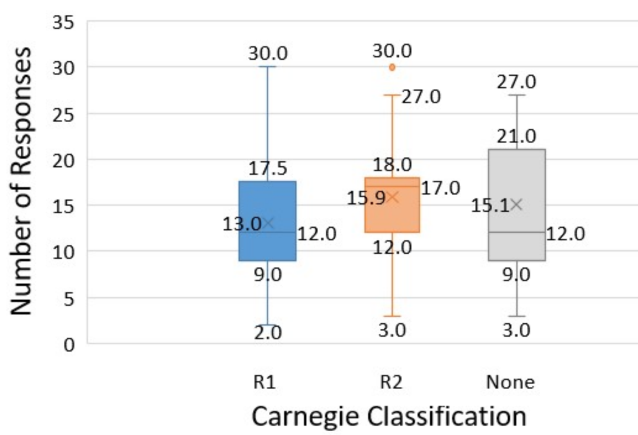

Figure 3: Respondents by Carnegie Classification versus Teaching Load in Hours

Research productivity

When faculty surveyed were asked, “Which of the following statements can be attributed to the impact on productivity?” A variety of answers were provided for them; including 1) I spend more time developing content for the classes, 2) I spend more time delivering the class content, 3) I spend more time in the mandatory training, 4) I spend less time on research, 5) I do not have access to lab equipment that would allow me to conduct research, 6) I do not have access to resources, 7) I do not have access to research equipment, 8) I am unable to interact with my graduate students, and 9) My interactions with students conducting research with me is reduced. There was an option to provide an answer. Five statements of the nine statements above reflect research, with the key impacts underlined (table 1).

Table 1

Research Productivity Impact by Carnegie Classification

Impact (based on statements above)	R1	R2	None
Research	16	5	8
Lab Equipment	5	1	4
Research Equipment	4	1	3
Graduate Students	5	3	1
Students	8	3	5

About a quarter of respondents reported spending less time on research during the pandemic R1: 16 of 55 (29.1%), R2: 5 of 23 (21.7%), and unclassified 8 of 31 (25.8%). Respondents also reported reduced time interacting with students conducting research R1: 8 of 55 (14.5%) R2: 3 of 23 (13.0%) and unclassified 5 of 31 (16.1%). While these are not large groups, this question allowed faculty to choose which impacts they felt. Respondents could choose multiple impacts, and not all faculty identified the same impacts. Interestingly, the percentages of respondents reporting research impacts is higher in R1 and non-classified institutions than those in R2 institutions.

Institutional Support

A comparison of the Carnegie Classification was made based on the faculty perception of institutional support. Respondents from institutions classified as R1 (53) indicated an average of 71.13 (Somewhat Good), a standard deviation of 24.09, a low value of 9, and a high value of 100. While respondents from institutions classified as R2 (23) indicated an average level of support of 73.30 (Somewhat Good), a standard deviation of 23.34, a low value of 20, and a high value of 100. Lastly, respondents from schools not classified (31) responded with an average of 72 (Somewhat Good), a standard deviation of 21.54, a low value of 20, with the highest being reported as 100. Based on this results it can be inferred that the Carnegie Classification did not generally affect the faculty perception of institutional support (during Covid-19)

Faculty surveyed were also asked, “Before January 2020, did the University offer resources that improved the delivery of content in an online medium?” Many universities offer internal educational support for faculty, including seminars, tutorials, and conferences which cover topics like Online Learning Environment (OLE). The majority of respondents from all classifications of universities indicated some level of resources for OLE prior to Covid-19 (table 2). Responses were quite different when asked if their Program/Department/College (Program) offered resources for OLE delivery. However, the largest group still responded in the affirmative (table 3). Based on the difference between the responses to these two questions, it can be inferred that most institutions (regardless of Carnegie Mellon Classification) assign OLE resources at the institutional level rather than the individual academic units.

Faculty surveyed were also asked, “Before January 2020, did the University offer resources that improved the delivery of content in an online medium?” Many universities offer internal educational support for faculty, including seminars, tutorials, and conferences which cover topics like Online Education (OLE). The majority of respondents from all classifications of universities indicated some level of resources for OLE prior to Covid-19 (table 2).

Table 2

By Carnegie Classification, (before January 2020) did the University offer resources that improved the delivery of content in an online medium?

Response	R1		R2		None	
Yes	44	(83.0%)	17	(74.0%)	23	(74.2%)
No	3	(5.7%)	3	(13.0%)	5	(16.1%)
No Knowledge	6	(11.3%)	3	(13.0%)	3	(9.7%)

Responses were quite different when asked if their Program/Department/College (Program) offered resources for OLE delivery. However, the largest group still responded in the affirmative (table 3).

Table 3

By Carnegie Classification, (before January 2020), did the Program/Department/College offer resources that improved the delivery of content in an online medium?

Response	R1		R2		None	
Yes	25	(47.2%)	12	(52.2%)	16	(51.6%)
No	21	(39.6%)	8	(34.8%)	4	(12.9%)
No Knowledge	7	(13.2%)	3	(13.0%)	11	(35.5%)

There is a substantial difference when considering the change in the perception of University support to Program support. The percent change from University support to Program support was determined (table 4). While all Carnegie Classifications had a large perception change from University support to Program support, R1 institutions showed the largest percent change. It is also interesting to note that respondents from institutions not classified (None) had the highest change to "No Knowledge" about their Program and the smallest percent change to "No." This is a concern which is easily remedied within individual Programs.

Table 4

By Carnegie Classification, Percent Change in Perception of Support from University to Program/Department/College

Response	R1	R2	None
Yes	43.2%	29.4%	30.4%
No	600.0%	166.7%	20.0%
No Knowledge	16.7%	0.0%	266.7%

While all Carnegie Classifications had a large perception change from University support to Program support, R1 institutions showed the largest percent change. It is also interesting to note that respondents from schools not classified (None) had the highest change to "No Knowledge" about their Program and the smallest percent change to "No." This is a concern which is easily remedied within individual Programs.

Conclusions

US construction faculty were surveyed to determine their perceptions of Covid-19 impacts to their research. The most of the faculty were affiliated with an institutions members of the Associated Schools of Construction (ASC). The faculty responses were compared on the basis of the Carnegie Classification. The result of the research indicates that there were no significant differences perception of Covid-19 impacts among faculty from R1, R2 and unclassified programs. This most probably due to the nature of study as the responders where using their own personal impression of the Covid-19 situation in relation to the situation prior to Covid-19.

One hundred and nine faculty responses were included in this study from all of the seven ASC Regions in the U.S. Fifty one percent of the responses were from associated with R1 institutions, twenty one percent of the responses were from faculty associated with R2 institution, and twenty eight percent of the responses were from faculty associated with unclassified institutions.

The average teaching load for faculty from all institutions was over 13 credit hours annually, which considering a traditional 3-hour course, is equivalent to an average of over four courses per year. Similarly, the Carnegie Classification did not appear to impact the number of credit hours taught by construction faculty. This is by itself also an interesting finding as R1 institutions are believed to have lower teaching load to compensate for the higher research expectation. This finding could be attributed that the construction discipline is still primarily seen as teaching programs and therefore requiring construction faculty to have a higher teaching load that their counterpart in the research institutions.

Faculty spending less time on research was the number one reason for research productivity impact, followed by the challenges that the faculty had to interact with students conducting research. This is an important finding, as faculty research activities are impacted even in situations not as extreme as Covid-19. It is not uncommon that faculty are assigned additional duties throughout the academic year which in turns reduces faculty time to work on research activities. Furthermore, sometimes faculty are not able to establish a regular meeting schedule with the student conducting research with them. Unfortunately, both of these situations, while detrimental to construction faculty research, are not unique to Covid-19. Thus, construction faculty and administrators should be mindful and more disciplined to maintain research productivity.

References

Adhikari, S., Mosier, R., & Langar, S. (2021a). Challenge of Delivering Construction Courses in an Online Environment Based on Faculty Experiences. EPiC Series in Built Environment. V.2, pg. 451-459.

Ahmed, S. M., Mahaffy, K. M., Forbes, L. H., Robinson-Watts, R. M., & Gregory, A. L. (2016). “Success Factors in Distance Education: A Case of Master of Construction Management at East Carolina University.” Proceedings of 123rd ASEE Annual Conference and Exposition, New Orleans, LA.

Alungbe, G., Mohammed, J., & You, Y. (2008). “Teaching Engineering Economy Online in Construction Program.” Proceedings of ASEE Annual Conference and Exposition, Pittsburgh, PA.

Associated Schools of Construction (ASC). (2022a). “General Information.” <https://www.ascweb.org/about/general-information/> Retrieved June 9, 2022.

Associated Schools of Construction (ASC). (2022b). “Regional Directory.” <https://www.ascweb.org/directory/regional-directory/> Retrieved July 29, 2022.

Carnegie Classification of Institutions of Higher Education. (2022). <https://carnegieclassifications.acenet.edu/> Retrieved September 22, 2022.

Centers for Disease Control and Prevention (CDC). (2020). Colleges, Universities, and Higher Learning: Considerations for Institutes of Higher Education. https://www.cdc.gov/coronavirus/2019-ncov/community/colleges-universities/considerations.html>

Clemmons, A., Lebovitz, L., Fulford, M., Greene, K., Franks, A., Branan, T., and Plake, K. I. (2022). "Impact of the COVID-19 Pandemic on Faculty at Research-intensive United States Schools/Ccolleges of Pharmacy." *Currents in Pharmacy Teaching and Learning*. V14. N.2. Pg.145-152.

Gable, G. G. (1994). "Integrating Case Study and Survey Research Methods: An Example in Information Systems." European Journal of Information Systems. V.3. pg.112–126.

Han, J., Yin, H., & Wang, J. (2018). "A Case Study of Faculty Perceptions of Teaching Support and Teaching Efficacy in China; Characteristics and Relationships." Higher Education. V.76. pg. 519-536.

Iwu C. G., Okeke-Uzodike, O. E., Anwana, E., Iwu, C. H., and Esambe, E. E. (2022). "Experiences of AcademicsWorking from Home during COVID-19: A Qualitative View from Selected South African Universities." *Challenges*. V.13. N.16.

Kelting, S., Holt, E. A., & Barry, N. (2016). "Peer and Student Review of an Online Construction Management Sustainability Course." Proceedings of ASEE Annual Conference and Exposition, New Orleans, LA.

Kinney, L., Liu, M., & Thornton, M. (2012). "Faculty and Student Perceptions of Online Learning in Engineering Education." Proceedings of 2012 ASEE Annual Conference, San Antonio, TX.

Langar, S., Adhikari, S., & Mosier, R. (2021). "COVID-19 Impacts on AEC Educators." EPiC Series in Built Environment., V.2. pg.597-605.

Langar, S., Mosier, R., & Adhikari, S. (2022a). "Perceptions and Pedagogical Responses of Construction Educators during COVID-19." International Journal of Construction Education and Research.

Langar, S., Mosier, R., & Adhikari, S. (2022b). "COVID-19 Impacts on Architecture Educators in India - A Review of Gender Perceptions." Proceedings of ASEE Annual Conference and Exposition, Minneapolis, MN.

Munoz-Najar,A., Gilberto Sanzana, A.G., Hasan, A., Cobo Romani, J.C., Azevedo, J.P.W.D., Akmal,M. (2022). "Remote Learning During COVID-19: Lessons from Today, Principles for Tomorrow (English)." Washington, D.C.: World Bank Group. http://documents.worldbank.org/curated/en/160271637074230077/Remote-Learning-During-COVID-19-Lessons-from-Today-Principles-for-Tomorrow

Schmidt, S., Hodge, E. & Tschida, C. (2013). "How University Faculty Members Developed Their Online Teaching Skills." Quarterly Review of Distance Education. V.14. N.3. pg.131.

Shea, P., Pickett, A., & Li, C. S. (2005). "Increasing access to Higher Education: A Study of the Diffusion of Online Teaching among 913 College Faculty." International Review of Research in Open and Distance Learning. V.6 N.2.

Sheehan, K. B. (2001). "Email Survey Response Rates: A review. Journal of Computer-Mediated Communication. V.6 N.2. JCMC621, https://doi.org/10.1111/j.1083-6101.2001.tb00117.x

Tabas, J. M., LeMay, C. M., & Freije, E. (2012). Online Education: The End of Learning. Proceeding of 2012 ASEE Annual Conference, San Antonio, TX.

University of California, Los Angeles, (UCLA). (2021). Voices from the Field: The Impact of COVID-19 on Early Career Scholars and Doctoral Students. Also available at <https://seis.ucla.edu/news/voices-from-the-field-the-impact-of-Covid-19-on-early> Retrieved October, 12, 2022.

Quantifying a Scoring Limitation of a Federal UAS Flight Proficiency Exam

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To operate a drone in the U.S., the federal government requires pilots to pass a standardized Federal Aviation Administration (FAA) knowledge test. The government does not require drone pilots pass a practical exam demonstrating minimum flight proficiency. However, the government, through the National Institute of Standards and Technology (NIST), has provided a voluntary exam protocol to test flight skills. Using the NIST exam protocol, the Airborne Public Safety Association has created the only nationally recognized unmanned aircraft systems flight proficiency certification. This certification is frequently used by contractors and construction UAS courses. The literature has identified a limitation in how the exam is scored. The purpose of this study is to quantify how impactful this limitation is. The researchers conducted an experiment administering the exam to 24 licensed drone pilots. The exam was scored compensating for the scoring limitation. The study found that when the scoring limitation was accounted for, scores were inflated by approximately 5% with inexperienced pilots. Inexperienced pilots will have the highest deviation and represent the most extreme cases. Given the relatively low 5% deviation with novice pilots, the study found that this limitation is not a significant concern and can be managed by the exam proctor.

Key Words: Drone, UAS, NIST, Assessment, APSA

Introduction

Unmanned aircraft systems (UAS), commonly referred to as "drones," are a rapidly expanding technology being used in a wide range of industries. The Federal Aviation Administration (FAA) reported that as of September 2022, over 865,000 drones had been registered and more than 280,000 remote pilots certified (FAA, 2021). In the past, the regulations governing commercial drone operations were very restrictive, requiring a Section 333 exemption from the FAA. The requirements to receive this exemption made it largely impractical for most private UAS operations. However, the release of U.S. Code of Federal Regulations Title 14 Part 107—Small Unmanned Aircraft Systems (Part 107) in 2016 made access to the national airspace by drone pilots significantly easier. One of the most significant requirements of Part 107 is passing the knowledge exam. The exam consists of

60 multiple-choice questions and is administered at third-party testing centers. The knowledge exam assesses a pilot's understanding of weather, regulations, airspaces, and a wide range of important UAS concepts. However, the exam does not include a practical component. Unlike Canada, the European Union, and Australia, the U.S. federal government does not require drone pilots to demonstrate minimum competency in operating an aircraft. The lack of a government-sponsored proficiency exam creates a challenge for the industry. Unlike most other licenses, there is no government standard that organizations can rely on to verify pilots are competent to operate the equipment. Contractors must either self-evaluate or rely on third-party credentialing. When companies self-evaluate, they absorb the cost of the assessment process and all of the legal exposure of determining flight competence. Contractors may wish to credential their pilots with third-party organizations; however, there is currently only one organization with a national reputation providing this certification.

The National Institute of Standards and Technology (NIST) is a laboratory under the U.S. Department of Commerce. It has developed several suites of testing protocols for robots, including UAS. The UAS testing protocols have the express purpose of "quantitatively evaluating various system capabilities and remote pilot proficiency" (NIST, 2020). NIST provides detailed instructions on how to build, administer, and score the exam. It does not provide scoring minimums, testing services, or certifications. The Airborne Public Safety Association (APSA) was founded in 1968 and is one of the most well-known and respected aviation associations. APSA has adopted the NIST Basic Proficiency Evaluation for Remote Pilots (BPERP) exam protocol to create a flight proficiency certification. It is the only nationally recognized flight proficiency certification currently available in the United States. Contractors often use it to validate their employees have sufficient skills to operate a drone on their company's behalf. It is also an assessment tool for construction management degree programs teaching drone technology.

Exam Scoring Limitation

The NIST BPERP test lane consists of a series of round targets at the bottom of two-gallon buckets. See Figure 1 left. Most of the targets are at a 45-degree angle with the ground. A proctor will give the pilots instruction on where to position their drone so that a particular target is visible with the on-board camera. If the drone is not directly in front of the target, the wall of the bucket will obstruct the view. Points are awarded only if the view of the target is "aligned" and not obstructed by the bucket wall. See Figure 1 right. The positioning instructions require the drone to be placed 10 feet horizontally and 10 feet vertically from the targets. If the pilot is in line with the target and precisely 10 feet (horizontally and vertically) with the target, then the camera will be at exactly 45 degrees with the ground, making the target perfectly aligned. Although this simple design has many advantages, a limitation is that this method awards points for the drone being in the correct *vector* instead of in the correct *position*. See Figure 2 for an illustration. The drone closest to the target is aligned and in the correct position. The second drone is also aligned but much further away and out of position. In the spirit of the exam, the pilot should not be awarded points. However, a strict interpretation of the scoring criteria requires points to be awarded because the target is visible even though it is significantly out of position. This limitation was first identified by Dees and Burgett (2022) and is the focus of this study.

Research Objectives

In the absence of a federal UAS practical exam, APSA has done the construction industry a significant service by providing a flight proficiency certification. Additionally, construction education programs, including the authors' home institution, use the APSA BPERP exam as part of their drone curriculum. Given the certification's value and the lack of alternatives, it is important to have confidence in how the exam is scored. This paper shows the results of an experiment where 24 Part 107 pilots were given the BPERP exam twice. The researchers recorded the attempts and compared the scores using traditional scoring practices and when a three-foot positional tolerance was imposed. The objective of the study is to evaluate if the scoring limitation identified in the literature has a meaningful impact on BPERP pass rates.

Figure 1. BPERP Targets (NIST 2021b)

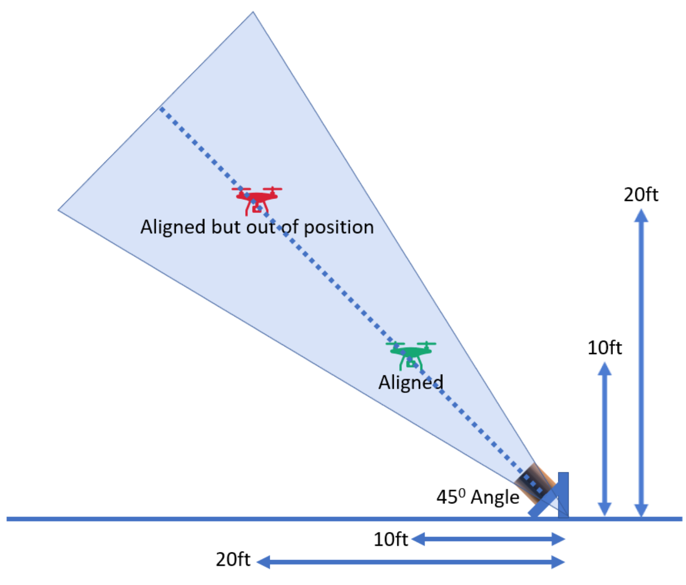

Figure 2. Scoring Limitation of BPERP

Background

Under Part 107, all pilots operating a UAS for commercial purposes must obtain a remote pilot certificate from the FAA. Earning the certificate, commonly referred to as the "drone license," requires pilots to demonstrate their drone erudition by passing a knowledge test. The test contains 60 multiple-choice questions administered over a 2-hour period. Topics assessed include Part 107 regulations, weather, aircraft loading, emergency procedures, airport operations, airspace, radio communication, and other UAS related procedures. Part 107 also requires commercial UAS pilots to take a recurrent online course provided by the FAA every 24 months. Demonstrating one's ability to operate a UAS is not required for licensure. This is considered by some to be a significant hole in the Part 107 license (Dees and Burgett, 2022). According to the Multi-Discipline Licensure Resource Project (MDLRP), a license "indicates that the professional has demonstrated the knowledge, skill and abilities to perform their services" (MDLR, 2022). Stated another way, a license validates the holder has sufficient 1) knowledge, 2) skill and 3) ability, to perform a specific task. Under the current Part 107 assessment criteria, "knowledge" is assessed but not practical "skills and abilities." Under the MDLRP definition, the Part 107 license does not comprehensively validate drone piloting competence. The APSA flight proficiency certification partially fills this gap. However, for the certification to have meaning, users must have confidence in the scoring metrics. Currently, this is not addressed in the literature and is the focus of this paper.

National Institute of Standards and Testing (NIST)

NIST is organized under the Department of Commerce and was originally founded by Congress in 1901 with the mission of removing major challenges to U.S. industrial competitiveness (NIST, 2021). NIST continues its mission by supporting smart electric power grids, microprocessor research, nanomaterials, and robot testing (NIST, 2021a). The Intelligent Systems Division within NIST developed the various UAS testing protocol including the BPERP. Although the BPERP test is evaluated in this study, the NIST Intelligent Systems Division has created multiple tests, including the Open Lane test, Obstructed Lane test, and First Responder UAS Endurance Challenge.

Airborne Public Safety Association (APSA)

APSA is a 501(c)(3) nonprofit membership organization. It was founded in 1968 and has over 3,000 members. Its primary mission is to support aircraft in public safety through networking, education workshops, publications, conventions, and product expositions. There is no formal relationship between the NIST Intelligent Systems Division and APSA. However, some individuals have concurrent dual employment with both organizations. NIST personnel have participated in APSA workshops when developing their flight proficiency certification. NIST personnel often mention APSA on public webinars and use it as a model when describing successful uses of the exams.

Basic Proficiency Evaluation for Remote Pilots (BPERP)

The BPERP exam is used for multirotor (hovering type) small UAS. It consists of three bucket stands, each with four, 2-gallon buckets placed around the perimeter. The buckets are positioned at a 45-degree angle with the ground and 90-degrees with each other. A fifth bucket is placed on top of the bucket stand angled straight up. The bucket stands are placed 10 feet from each other, and the pilot is required to fly at an altitude of 10 feet. Round targets are placed at the bottom of the buckets. During the exam, a proctor will read off 40 instructions directing the pilot where to position the drone and which target to take a picture of. The pictures of the targets are reviewed after the exam, and a point is awarded if the green ring is unbroken. See Figure 1. The first 20 positions/points are referred to as the position phase of the test and are shown in Figure 3 on the left. The second 20 positions/points are referred to as the traverse phase and are shown in Figure 3 on the right. To earn the APSA flight proficiency certification, a pilot must earn 32 points (80%) within 10 minutes. For more information on the BPERP exam, please visit the NIST UAS Test Methods page.

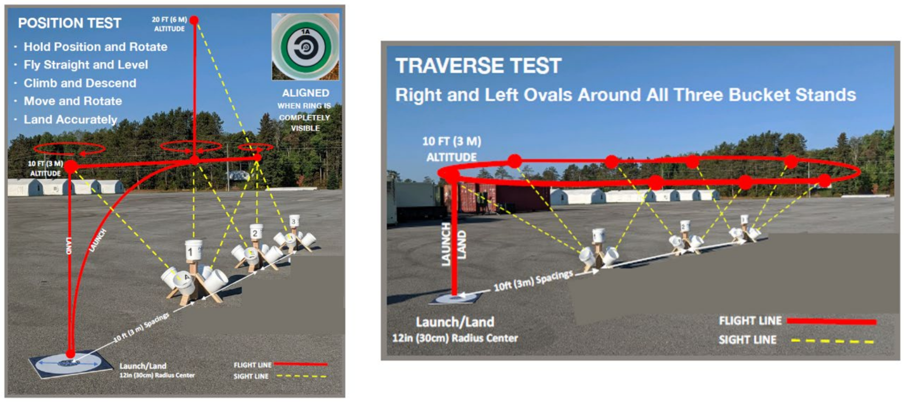

Figure 3. BPERP Positions (NIST 2020)

Gap in the Literature

The literature shows that drones are being used to support a wide range of activities (Gheisari et al., 2014; Lucieer et al. 2014; Rakha et. al., 2018). Some of the more common uses of drones in construction includes inspections (Tatum & Liu, 2017; Li & Liu, 2019), surveying (Aiyetan & Das, 2022; Adjidjonu & Burgett, 2021), and creating as-builts (Varbla et al., 2021; Hubbard, & Hubbard, 2020). The literature is nearly silent on scholarly studies addressing drone licensure and certification challenges. One notable exception is the work of Dees and Burgett (2022). Dees and Burgett make the case that the FAA Part 107 exam is important; however, it does not address flight competence comprehensively. The lack of standardized flight proficiency testing is "a significant risk for contractors using drones" (Dees and Burgett, 2022). The Dees and Burgett study experiment used similar bucket stand apparatus used in the BPERP test. Their study was the first to identify the scoring limitation of the NIST-based test. However, they stopped short of evaluating if the scoring limitation had a meaningful effect on pass rates. This is a critical gap in the literature. The APSA BPERP exam is the only nationally recognized flight proficiency certification. For it to have meaning, it is critical to have confidence in how it is scored. Evaluating if the known scoring limitation of the exam is impactful to pass rates and filling this gap in the literature is the focus of this paper.

Methodology

A sample of 24 Part 107 pilots were recruited for the study. The pilots primarily worked for government agencies throughout the state. The pilots completed a survey prior to the study that asked questions about their experience. The pilots were largely inexperienced, which was ideal for this study. Pilots with significant experience would be able to position their drone well and have scores less impacted by an imposed tolerance. Inexperienced pilots who do not have the muscle memory to position a drone well would be the ideal group for testing the boundaries of a positional tolerance. As such, inexperienced pilots were recruited because they will provide the outer most range for how impactful the scoring limitation is.

An experiment was developed where pilots completed the BPERP exam in person using traditional methods and with a computer simulator developed by the research team. Flight performance scores and times measured with the simulator have been shown to be statistically the same as with in-person testing (Dees & Burgett, 2022). The in-person test was administered on an intermural soccer field at the research team's home institution. Three NIST Open Test Lanes were set up on the field. The research team supplied DJI Mavic 2 Pro and DJI Phantom 4 Pro model drones for the experiment. The weather conditions during the experiment were warm, sunny, and with very little wind. The proctors provided positional instructions but did not correct pilots for flying beyond the specified 10-foot distance.

A critical piece of the study was to measure the actual distance between the target and the drone when an image was captured and compare that to the specified 10-foot requirement. The distance for the in-person exam was measured by recording the exam with a second drone in a hover 250 feet above the test lane. The distance was measured by overlaying a scaled grid over the video. See Figure 4. This method does not allow for the measurement of the vertical distance. However, the altitude of the drone is provided on the drone controller screen and is thus less of an unknown variable.

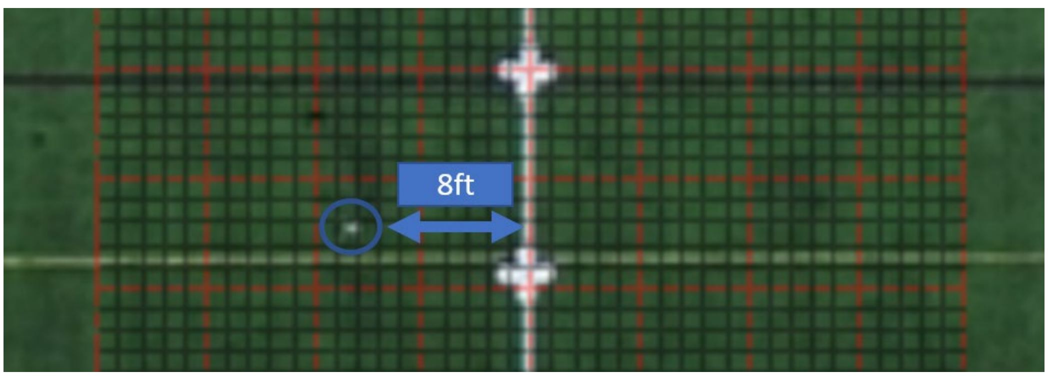

Figure 4. Measuring "S" distance with video

Immediately after the pilots completed the in-person BPERP test, they went to the research team's lab located a short drive away. Three simulator stations were set up for the participants to take the same BPERP test in the virtual environment. See Figure 5. The simulator self-proctors the exam with prerecorded audio, text instructions, and automatic scoring. The simulator also records the distance from the target when an image is virtually captured.

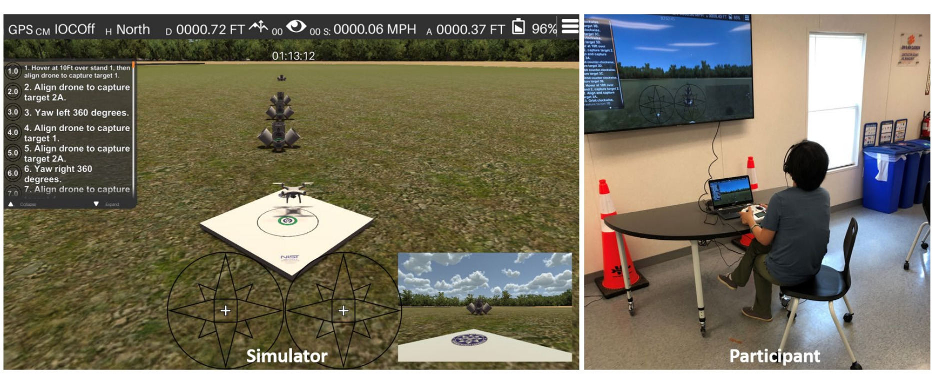

Figure 5. Simulator NIST Basic Maneuvering test

If the drone was closer than seven feet or farther than 13 feet from the target when an image was captured, that point would be disqualified even if the entire green ring was aligned. The three-foot value was developed subjectively but in consultation with industry experts. The test takers' raw scores and when a three-foot tolerance was imposed were compared.

Results

The study found that the average scores were not significantly impacted when a three-foot tolerance was imposed. The average score of the in-person and virtual BPERP was 36.4 out of 40 points. When a three-foot tolerance was imposed, the average score decreased to 34.6 points. That is a 1.8-point difference or approximately 4.5%. See Table 1.

Table 1

BPERP Scoring Comparison

Points Scored	In-Person Average	In-Person Min/Max	Simulator Average	Simulator Min/Max	Average Score
Traditional Method	38.7	33/40	35.3	19/40	36.4
3-ft Tolerance Imposed	34.3	23/40	34.8	19/40	34.6
Difference					1.8Pts/4.5%

Over three quarters of the exams taken had either zero or one point disqualified because the image was captured beyond the three-foot tolerance. Approximately 9% of the exams had two or three points disqualified. Several pilots lacked basic flight skills and had seven or eight points disqualified due to tolerance violations. See Table 2 for a breakdown of the frequency of point disqualification.

Table 2

Frequency of Point Disqualification Because of Tolerance Violation

Number of Points Disqualified	0	1	2	3	4	5	6	7	8
Percentage of Exams	58%	19%	6%	3%	3%	0%	0%	6%	6%

Conclusions

The study participants were inexperienced pilots working for state and local government agencies. Inexperienced pilots were ideal for this study because they will have a disproportionally large number of points disqualified if a positional tolerance was imposed compared to experienced pilots. This group would provide the "worst case" in quantifying the scoring limitation's impact. The experiment demonstrated that even in the worst-case scenario with inexperienced pilots, scores were exaggerated by less than 5%. Most of the exam takers (77%) had one or no points disqualified. This study found the scoring limitation is relatively minor and for routine testing is negligible. However, when the test is used for higher-level functions such as a final exam in a drone course or for an organizational certification, it is important to manage the scoring limitation.

Discussion

The most practical way to manage positional error is with the proctor in the field. Proctors should be aware of the limitation and given instructions to either notify test takers when they exceed the given tolerance or make notes to disqualify points after the exam. It can be difficult to "eyeball" precise distances in the field. One way to assist with this is to provide parallel lines 10 feet on either side of the test lane. These lines, which can be made with paint or a length of rope, can be used as a guide for the proctor to gauge distance. A disadvantage of this is that they also provide a visual aid to the pilot. This aid is not explicitly prohibited in the NIST instructions, but it diminishes the exam's rigor. A second option is to use a second proctor who can move around the lane to better estimate distance as the drone navigates the targets. This increases the cost and complexity of coordinating the test, however.

It is worth noting that the virtual BPERP administered on the simulator automatically imposes a three-foot tolerance without any additional measures. The exam is self-proctoring and records the results in the cloud. The only virtual BPERP currently available is on the Zephyr simulator produced by Little Arms Studios. APSA has adopted the Zephyr BPEPR as an acceptable alternative for in-person proctoring. The researchers use this simulator to credential their students taking an online UAS course. The software is available to other institutions for a fee.

References

Adjidjonu, D., & Burgett, J. (2021). Assessing the accuracy of unmanned aerial vehicles photogrammetric survey. *International Journal of Construction Education and Research*, *17*(1), 85–96.

Aiyetan, A. O., & Das, D. K. (2022). Use of drones for construction in developing countries: Barriers and strategic interventions. *International Journal of Construction Management*, 1–10.

AOPA. (2019). *2019 state of general aviation*. Retrieved October 14, 2020, from http://download.aopa.org/hr/Report_on_General_Aviation_Trends.pdf

Dees, C., & Burgett, J. (2022). Using flight simulation as a convenient method for UAS flight assessment for contractors. *The Professional Constructor*, *47*(1).

Federal Aviation Administration. (2022). *UAS by the numbers*. Retrieved September 29, 2022, from https://www.faa.gov/uas/resources/by_the_numbers

Gheisari, M., Irizarry, J., & Walker, B.N. (2014). UAS4SAFETY: The potential of unmanned aerial systems for construction safety applications. In *Proceedings of the Construction Research Congress 2014* (pp. 1801–1810).

Hubbard, B., & Hubbard, S. (2020, July). Opportunities for transportation departments to leverage construction UAS data. In *Creative Construction e-Conference 2020* (pp. 20–26). Budapest University of Technology and Economics.

Li, Y., & Liu, C. (2019). Applications of multirotor drone technologies in construction management. *International Journal of Construction Management*, *19*(5), 401–412.

Lucieer, A., S.M. de Jong, and D. Turner. (2014). Mapping landslide displacements using Structure from Motion (SfM) and image correlation of multi-temporal UAV photography. *Progress in Physical Geography*, *38*(1), 97–116.

Multi-Discipline Licensure Resource Project. (2022). *Why is licensure important?* Retrieved October 4, 2022, from https://licensureproject.org/psychology/why-is-licensure-important

National Institute of Standards and Technology. (2020). *Standard test methods for small unmanned aircraft systems*. Retrieved October 11, 2021, from https://www.nist.gov/system/files/documents/2021/06/17/NIST%20sUAS%20Open%20Test%20Lane%20-%20Quick%20Start%20Trifold%20%282020D%29.pdf

National Institute of Standards and Technology. (2021a). *About NIST*. Retrieved October 11, 2021, from https://www.nist.gov/about-nist

National Institute of Standards and Technology. (2021b). *Measuring and comparing small unmanned aircraft systems capabilities and remote pilot proficiency*. Retrieved October 11, 2021, from https://www.nist.gov/system/files/documents/2020/07/06/NIST%20sUAS%20Test%20Methods%20-%20Introduction%20%282020B1%29.pdf

Rakha, T., & Gorodetsky, A. (2018). Review of Unmanned Aerial System (UAS) applications in the built environment: Towards automated building inspection procedures using drones. *Automation in Construction, 93*, 252–264. https://doi.org/10.1016/j.autcon.2018.05.002

Tatum, M. C., & Liu, J. (2017). Unmanned aerial vehicles in the construction industry. In *Proceedings of the Unmanned Aircraft System Applications in Construction, Creative Construction Conference* (pp. 19–22). Primosten, Croatia.

Varbla, S., Puust, R., & Ellmann, A. (2021). Accuracy assessment of RTK-GNSS equipped UAV conducted as-built surveys for construction site modelling. *Survey Review*, *53*(381), 477–492.

An Online Drone Course for Construction Management Students: Curriculum, Simulation, and Certifications

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It is incumbent upon higher education institutions to teach students how to use emerging technologies and best practices of advanced workflows. Unmanned aircraft systems (UAS) are rapidly expanding tools that support various industries, including construction management, civil engineering, and surveying. There are many challenges to offering a course focused on the use of an outside, hands-on tool. These challenges can be exacerbated by the online delivery method. This paper describes the curriculum and delivery method of an online drone course taught at a large land grant institution in the southeast. The course allows students to earn their FAA Part 107 remote pilots certificate and their Airborne Public Safety Association (APSA) flight proficiency certification, and it prepares them to become a Level 1 UAS thermographer. This paper will indicate where this institution has found success and where future development is needed when offering this course online. The paper can also be a roadmap for other schools to create a similar UAS course.

Key Words: Online Course, Drones, UAS, Simulation, Certifications

Introduction

Unmanned Aircraft Systems (UAS), commonly referred to as "drones," are an emerging technology that supports many industries. Only a short time ago, drones were a novelty rarely seen in practical application. The FAA significantly restricted access to the national airspace for commercial drone purposes. This regulator barrier all but stifled the development of cost-effective hardware and the development of supporting software applications. However, there was a seismic shift in the drone community with the release of CFR Title 14 Part 107 (Part 107) in 2016. Part 107 removed most of the regulatory barriers and opened the national airspace to the public. This led to the development of affordable prosumer hardware and high-powered software applications tailored to individual industries. In less than seven years, drones have gone from an experimental novelty to a critical part of many contractors' marketing, estimating, and project management workflows.

Universities have a long history of researching new technologies and preparing their graduates to use them (Harper, et al., 2022). The use of UAS in the construction industry is no different. Several ASC schools have created elective drone courses for their students. However, because of the newness of the technology, there is a significant gap in the literature related to UAS-based curricula and case studies of successful drone classes. This paper will help fill this gap by describing a drone course delivered by a major land grant institution in the Southeast. While there are a few UAS-course case studies available in the literature, this paper is unique because it describes the curriculum of a fully online course exclusively focused on UAS use in the built environment. Moreover, the course is promoted as "comprehensive" because it provides students with FAA licensure, flight skills certified by a nationally recognized public safety organization, and critical UAS skills such as photogrammetry and thermography. Universities wishing to create a UAS program can adopt or modify the curriculum described in this paper for their specific purposes.

Literature Review

Drones have a wide range of use cases, including cinematography, search and rescue, plant monitoring, and surveillance. Despite the relative newness of the technology, the literature is well-populated with descriptions of how the construction industry has used the technology for safer and more productive jobsites. Common uses include safety inspections, site management, and surveying (Lie & Liu, 2019). A more detailed list of drone uses in the construction industry can be found in Table 1.

Published Drone Course Case Studies

Several schools have published their experiences incorporating drones into their construction management programs. A local contractor helped incorporate UAS technology into Youngstown State University's civil and construction engineering program (Sanson, 2019). Texas A&M created a drone course that included FAA regulations, safety, insurance, and 3D mapping (Williamson & Gage, 2019). The focus of this course was using drones to support surveying activities, as well as learning about the regulatory challenges experienced during the initial release of Part 107. Irizarry published a case study in 2019 highlighting the success Georgia Tech had in incorporating drones at the graduate level. This case study underscored the importance of understanding government regulations applied to UAS education. It also made the reader aware of the challenges associated with operating a drone on a campus located in a major metropolitan area.

As an alternative to offering a course solely focused on UAS technology, some schools have adopted the approach of adding drone modules into existing courses. A California Polytechnic State University paper proposed that courses focusing on construction surveying, heavy civil construction management, and emerging technologies are well suited for incorporating a UAS curriculum (Sanchez, 2021). The University of Florida followed this model and integrated a UAS module into an undergraduate Building Information Modeling course (Pereira et al., 2018). The module focused on photogrammetry and showed how it could be used to support model updates.

These case studies indicated several common challenges to the incorporation of UAS technology into their curriculum. Part 107 limits where drones can be operated based on airspace classification.

Schools in proximity to major airports may not be permitted to fly drones outside, making the instruction of practical flight skills difficult. Even when airspace classification wasn't an issue, acquiring university approval to operate a drone was a common challenge at some institutions. The cost of the equipment was also a common challenge mentioned. Limited administrative support, faculty training, low industry support, and lack of a program champion have also been listed in the literature as challenges (Harper et al., 2022).

Table 1

Summary of How Drones Are Being Used in Construction

Activity	Citation No.
Mapping	6
Inspection	1, 4, 5, 7, 8, 10
Safety	1, 4, 6, 7, 8, 14
Surveys	1, 2, 3, 4, 5, 6, 7, 9, 11
As-Built	11, 12, 13
BIM	3, 4, 7, 13
Marketing	10
Automated Assembly	1
Material Delivery	7, 10
Thermal Imaging/Scanning	2, 5, 10, 11
Photography	1, 2, 3, 4, 6, 9, 10, 11, 12, 13
Monitoring	7, 8, 10, 12, 13

1) Tatum & Liu, 2017; 2) Williamson & Gage, 2019; 3) Irizarry, 2019; 4) Zaychenko et al., 2018; 5) Agapious, 2021; 6) Aiyetan & Das, 2022; 7) Li & Liu, 2019; 8) Howard et al., 2018; 9) Adjidjonu & Burgett, 2021; 10) Cajzek & Klansek, 2016; 11) Varbla et al., 2021; 12) Bognot et al. 2018; 13) Anwar, et al., 2018

Drone Course Curriculum

The published case studies have common curriculum topics, including Part 107 regulations, flight skills, photogrammetry and volumetrics, surveying, and BIM. However, the literature does not specify which topics are, or should be, taught in a construction management drone class. Burgett surveyed 50 contractors, asking them to rate curriculum topics based on usefulness (2021). In addition to the topics addressed in the other case studies, the Burgett survey found that contractors also saw value in teaching students how to use pre- and post-flight checklists, how to file FAA accident reports, how to file air traffic authorization requests, how to file FAA waivers, how to use UAS-specific weather tools, and how to program autonomous (autopilot) missions.

The most comprehensive survey of drone-related curricula in construction management and civil engineering programs was conducted by Harper et al., (2022). Over 1,300 survey invitations were sent through the ASC and ASEE listservs, and 92 were returned. Of the 92 returned survey questionnaires, only 22 (12 engineering and 10 construction programs) indicated that they were currently using UAS in the classroom. The most common skills taught were photogrammetry, measuring quantities, and site mapping and layout. Surveying, BIM, inspections, tracking work progress, quality control, positioning and navigating a UAV, tracking resources, and inventory management were also taught in some programs.

Online Drone Course

The instructor's drone course is the only UAS-specific class consistently offered at his home institution. With a traditional on-ground course, the number of students that could be enrolled is limited by lab space, the number of drones available, and the physical limitations of supervising too many students flying at the same time. However, in an online environment, these limitations are removed. The objective of the course was to make this course available to as many students as possible from across a wide range of disciplines. As a result, it had no prerequisites and was offered asynchronously.

The class was divided into five topic areas each with corresponding modules. The specific topics and modules are provided in table 2. Each module contained video tutorials, readings from a course workbook, and various assignments and lab exercises. The video tutorials were recorded using Articulate Storyline. Articulate Storyline is an e-learning platform that has an end product similar to a well-animated PowerPoint presentation. However, it also includes periodic knowledge check questions and embedded resources. The instructor wrote the Basic UAS Reference Guide and Manual (B.U.R.G. manual) as a course workbook. It provided step-by-step instructions for all the assignments and lab exercises. The instructor expected that as time went on, the students would forget some of the tools used in the class. The hope was that students would keep the B.U.R.G. manual and use it as a reference guide in the field after they graduated. The instructor held optional web calls at the beginning of each week. These calls often lasted 15 minutes and included only the instructor's review of the required deliverables for the week. However, some calls lasted longer when a student presented questions or needed additional clarification. The calls were recorded, and the links were provided in the class.

Part 107

A Part 107 requirement is that commercial drone pilots must pass a knowledge test and earn their remote pilot certificate. The knowledge test includes 60 multiple-choice questions over two hours given at a third-party testing site. The exam fee is approximately $175. The first five modules of the course were focused on preparing students to pass this test. The first assignment of Module 1 was to provide documentation that the exam was scheduled by the end of Module 5. Student feedback typically included comments like "nothing is as motivating as a deadline." Knowing the date also allowed the instructor to provide an encouraging email the morning of their exam. The FAA provides a Part 107 Study Guide (Federal Aviation Administration [FAA], 2016). The study guide is not a body of knowledge, however, and does not contain sufficient information to guarantee success on the exam. The video tutorials are structured around the chapters of the study guide. They reinforce the material in the text and provide the missing information needed to pass the exam. The modules contain hundreds of sample questions with automated feedback. Students were required to complete two practice exams that simulated the actual exam. After students took the FAA exam, they uploaded their results. Their performance on the FAA exam accounted for 25% of their overall course grade. The course had 16 students in which 12 (75%) passed the FAA exam. See table 3.

Table 2

Course outline with topics and certifications issued

Topic	Wk.	Module	Certification Issued
Part 107 Regulation and Knowledge Test Preparation	1	Introduction	FAA Remote Pilot Certificate
	2	Ch. 1 & 2 of FAA Study Guide	
	3	Ch. 3A, 3B & 4 of FAA Study Guide	
	4	Ch. 5 - 12 of FAA Study Guide	
	5	FAA Part 107 knowledge test	
Regulatory Compliance Tools	6	FAA waiver, accident reporting, weather tools, and LAANC	
Flight Training	7	Flight training with simulator	APSA Flight Proficiency Certificate
	8	Flight training with simulator	
	9	BPERP examination	
Photogrammetry	10	Data collection, photogrammetry, and intro to Drone Deploy	
Thermography	11	Photogrammetry with DroneDeploy	Level 1 UAS Thermography Certificate
	12	Thermal dynamics & movement, IR fundamentals, and emissivity	
	13	IR cameras, palettes, FOV and thermal tuning	
	14	Standards, IR applications, and UAS night operations	
	15	Level 1 Thermography Exam	

Table 3

Number of Students who Earned the Certificates Associated with Class

	Total Students	FAA Part 107 Knowledge Test	APSA Flight Proficiency Test	Level 1 UAS Thermography Exam
Passing Exam	16	12 (75%)	16 (100%)	11 (69%)

Compliance Tools

The part 107 exam assesses the pilot's knowledge of various rules. The *FAA-CT-8080-2H* booklet published by the FAA contains sectional charts selections, aeronautical weather forecasts, and other sample data. This booklet accompanies the exam, and students must refer to it to answer many questions. This approach works well for a basic assessment; however, it is important for students to be able to check airspaces, temporary flight restrictions, and UAS-specific weather forecasts in the real world. The focus of Module 6 is to teach practical online and app-based tools to comply with Part 107 regulations. See table 2 for a list of specific topics addressed.

Flight Simulator

Flight skills are the primary focus of Module 7, 8 and 9. Given that this is an online delivery, all the fight training is completed with a computer simulator. A license to operate the Zephyr Drone Simulator (zephyr-sim.com) and a FlySky FS-i6S controller are provided to the students to use on their personal computers. The simulator includes over 50 unique drone missions and approximates the physics of 14 of the most commonly used commercial UAS. An advantage of using Zephyr in the institutional setting is that the student performance is automatically uploaded to the cloud, where the instructor can see hours logged, mission scores, and detailed flight performance data.

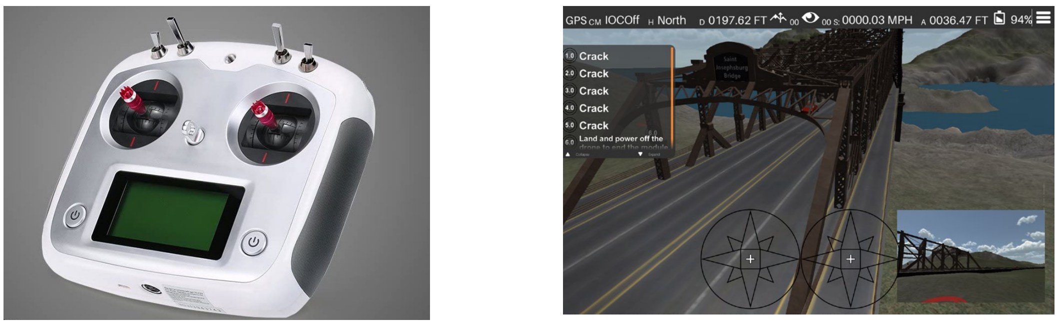

Figure 1. Controller and Zephyr Simulator

Flight performance is not assessed with the FAA licensure. However, the Airborne Public Safety Association (APSA) has adopted the federal government's Basic Proficiency Evaluation for Remote Pilots (BPERP) exam for flight proficiency certification. APSA's BPERP certification is the only nationally recognized credential for UAS flight proficiency. Traditionally, the BPERP exam is given in person by a certified APSA proctor. Pilots must navigate a course and take pictures of targets at the bottom of 2-gallon buckets. The instructor has worked with APSA and Zephyr to offer the BPERP exam through the simulator. One limitation is that an APSA proctor must review and certify the test results before a certification can be earned. The instructor has gone through the APSA training to become a proctor, so he can certify his students' BPERP scores. The certification comes from APSA at the cost of approximately $75. All 16 students passed the BPERP examination and earned their APSA certificate. See table 3.

Photogrammetry

The tenth module of the course focuses on creating 3D maps and models from drone data. The course provides students a license to use DroneDeploy, one of the leading flight control and photogrammetry software applications. The flight control application allows students to create waypoint-assisted missions for data collection. The app has a built-in simulation that will mimic the mission programmed without actually being connected to the drone. DroneDeploy's photogrammetry application is web based. This is particularly useful in an academic setting because students don't need a high-powered computer to operate it. The instructor provides students with sample data, and the students then create 2D orthophotos and 3D models. They are asked to extract quantity takeoff data from the models they create. There is also a surveying component where the students are provided with geolocated ground control points. Students are shown that adding ground control points can have minor improvements in relative accuracy but improve absolute accuracy by feet if not more.

Thermography

An emerging use case for drone technology is aerial thermography. Drones with high-resolution infrared imagers are being used more frequently by contractors to detect roof leaks, build energy audits, and perform various quality control activities. However, like most sophisticated equipment, the user needs training to operate it. This is especially true with infrared images. There is more to thermography than identifying “blue as cold and red as hot.” Figure 2 shows a piece of plywood with two different coatings. Both coatings have the same temperature but significantly different infrared profiles. Modules 11 through 15 focus solely on UAS thermography. The curriculum was developed based on the recommendations of the American Society for Nondestructive Testing (ASNT) document SNT-TC-1A. It specifically addresses basic thermodynamics, the science of infrared radiation, emissivity, thermal image tuning, camera operations, thermal loading, and various infrared related standards.

A significant portion of the thermal modules focuses on using software to tune thermograms by adjusting emissivity and environmental conditions. The course uses DJI’s Thermal Analysis Tool for this application. DJI is the largest commercial drone manufacturer and commands approximately three-quarters of the commercial drone market (Statista, 2022). Thermograms from DJI thermal cameras can only be tuned by their proprietary software. The DJI Thermal Analysis Tool is limited compared to other thermal tuning software, but it has the advantage of being free to use.

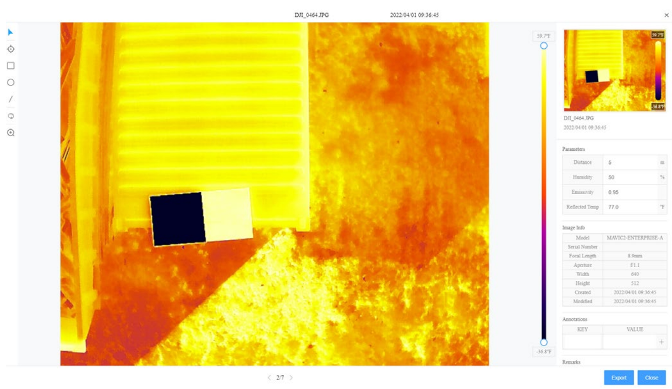

Figure 2. DJI Thermal Analysis Tool

While not part of the recommended ASNT curriculum, the course also addresses specific considerations for the operation of a UAS at night. Most building-related infrared inspections are conducted at night, making this a critical topic to address. Because the instructor is a certified Level 3 thermographer, he is qualified under ASNT standards to develop the curriculum and certify the examination to credential his students as Level 1 thermographers. Eleven students (69%) earned the minimum 80% required to receive their Level 1 UAS Thermography certification. See table 3.

Conclusions

This paper provides describes how drones are being taught online at a large university in the Southeast. The course is promoted as a comprehensive UAS course because it provides all the basic skills to operate a small UAS in the national airspace. Specifically, the main curriculum topics include Part 107 licensure, regulatory compliance tools, flight skills through simulation, photogrammetry, and UAS thermography. The course provides students with three certifications which include 1) the FAA Part 107 Remote Pilots Certificate, 2) APSA BPERP flight proficiency certification, and 3) becoming a level 1 UAS thermography. This paper can be used as a road map to create a similar drone course at other universities. Interested faculty are encouraged to contact the author for additional information and collaboration.

Future Work

The instructor is exploring a second UAS class to follow the course described in this case study. One activity that would be taken to a higher level would be creating an FAA Part 107 waiver application. The photogrammetry modules would be expanded to address advanced accuracy diagnostics and surveying best practices. Multispectral sensors mounted on drones have been shown to detect plant health and have numerous agricultural applications. Flight skills would continue to be developed in the second class. APSA provides a certification beyond the BPERP using an obstructed test lane. This advanced certification is being considered for the second class. Finally, developing the coursework for students to become Level 2 or 3 thermographers is also being explored. In addition, a future study is planned to evaluate if student learning retention is impacted with an online delivery method.

References

Adjidjonu, D., & Burgett, J. (2021). Assessing the accuracy of unmanned aerial vehicles photogrammetric survey. *International Journal of Construction Education and Research*, *17*(1), 85–96.

Agapiou, A. (2021) Drones in construction: An international review of the legal and regulatory landscape. *Proceedings of the Institution of Civil Engineers–Management, Procurement and Law 174*(3): 118–125. https://doi.org/10.1680/jmapl.19.00041

Aiyetan, A. O., & Das, D. K. (2022). Use of drones for construction in developing countries: Barriers and strategic interventions. *International Journal of Construction Management*, 1–10.

Anwar, N., Izhar, M. A., & Najam, F. A. (2018, July). Construction monitoring and reporting using drones and unmanned aerial vehicles (UAVs). In the *Tenth international conference on construction in the 21st century* (pp. 2–4).

Bognot, J. R., Candido, C. G., Blanco, A. C., & Montelibano, J. R. Y. (2018). Building construction progress monitoring using unmanned aerial systems (UAS), low-cost photogrammetry, and geographic information systems (GIS). *ISPRS Annals of Photogrammetry, Remote Sensing & Spatial Information Sciences*, *4*(2).

Burgett, J. (2021). An industry focused course to address barriers and benefits of drones in construction. *EPiC Series in Built Environment*, *2*, 210–218.

Cajzek, R., & Klanšek, U. (2016). An unmanned aerial vehicle for multi-purpose tasks in construction industry. *Journal of Applied Engineering Science*, *14*(2), 314–327.

FAA. (2016). *Remote pilots—Small unmanned aircraft systems study guide*. FAA-G-8082-22.

FAA. (2022). *Chart supplements: Basic search*. https://www.faa.gov/air_traffic/flight_info/aeronav/digital_products/dafd/search/

Harper, C. M., Mehany, M., & Parajuli, M. (2022). Unmanned aircraft vehicles in construction and engineering higher education programs. In *Construction Research Congress 2022* (pp. 90–99).

Howard, J., Murashov, V., & Branche, C. M. (2018). Unmanned aerial vehicles in construction and worker safety. American journal of industrial medicine, 61(1), 3-10.

Hubbard, B., & Hubbard, S. (2020, July). Opportunities for transportation departments to leverage construction UAS data. In *Creative Construction e-Conference 2020* (pp. 20–26). Budapest University of Technology and Economics.

Irizarry, J. (2019). Use of small unmanned aerial systems in construction management curriculum in compliance with FAA regulations: A case study. In *55th ASC Annual International Conference Proceedings*.

Li, Y., & Liu, C. (2019). Applications of multirotor drone technologies in construction management. *International Journal of Construction Management*, *19*(5), 401–412.

Pereira, E. R., Zhou, S., & Gheisari, M. (2018). Integrating the use of UAVs and photogrammetry into a construction management course: Lessons learned. In *Proceedings of the International Symposium on Automation and Robotics in Construction* (Vol. 35, pp. 1–8). IAARC Publications.

Sanchez, A. (2021). Proposal for purchase of in-house drone for Cal Poly's construction management department. Retrieved October 11, 2022, from https://digitalcommons.calpoly.edu/cgi/viewcontent.cgi?article=1538&context=cmsp

Sanson, J. (2019, February). *Drone use in the construction industry leads to integration into the current civil and construction engineering technology*. [Curriculum Paper] 2019 CIEC, New Orleans, LA. https://peer.asee.org/31517

Statista. (2022). *Global market share of consumer and commercial drone manufacturers in March 2021, based on sales volume*. Retrieved October 14, 2022, from https://www.statista.com/statistics/1254982/global-market-share-of-drone-manufacturers/

Tatum, M. C., & Liu, J. (2017, June). Unmanned aerial vehicles in the construction industry. In *Proceedings of the Creative Construction Conference*, Primosten, Croatia (pp. 19–22).

Varbla, S., Puust, R., & Ellmann, A. (2021). Accuracy assessment of RTK-GNSS equipped UAV conducted as-built surveys for construction site modelling. *Survey Review*, *53*(381), 477–492.

Williamson III, K. C., & Gage, G. (2019). Important considerations for implementing a drone-based activity within a construction surveying course. In *55th ASC Annual International Conference Proceedings*.

Zaychenko, I., Smirnova, A., & Borremans, A. (2018). Digital transformation: The case of the application of drones in construction. In *MATEC web of conferences* (Vol. 193, p. 05066). EDP Sciences.

Ensuring operational performance for promoting sustainable practices in Public Private Partnership (PPP) projects in the UK

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A great deal of focus has been placed by different governments on their construction industries as it is known for being a large polluter of the planet, as well as being a huge consumer of energy and emitter of carbon. The research was completed by investigating major PPP themes related to UK (namely, challenges to UK construction, operational performance of PPP projects, and drivers of PPP projects). To ensure enough participants were reached, the snowball sampling technique was used to collect data from 156 industrial professionals. Relative importance index (RII) analysis was performed to check the ranking of the factors, and to determine the significance of each factor. This analysis revealed a large significance on time and cost management issues within the challenges to UK construction section. Sustainability presented highly significant results relating to modern methods of construction like BIM as well as the use of modern schemes such as the PF2 (Private Finance 2) scheme. This was also found to be an important factor in the operational performance of PPP projects as well as resolving financial and fiscal issues within the public sector. This research can support public and private sectors to develop advanced collaborative networks to boost productivity.

Key Words: Private Public Partnership, Sustainable Practices, Operational Performance, Construction Projects, United Kingdom

Operational Performance in PPP Projects

Operational performance is defined by Azim and Ahmed (2015) as the "measurable aspects of the outcomes of an organization's processes, such as reliability and production cycle time". To ensure operational performance of a project, there must be a presence of various success factors to streamline the process. Haryati and Habib (2018) conducted a study on the critical success factors of PF2 projects in the UK. They discovered that there were 26 success factors that could influence the operational performance of PPP projects under the PF2 scheme. These were split into 5 sections. The sections, and an example of a success factor under that section, has been highlighted below:

- Political environment and regulatory - Favourable legal framework
- Economic factor - Available financial market
- Collaborative working relationship - Shared authority between the public and private sector
- Project management - Appropriate risk allocation
- Skills, experience, and competency - Continued use and growth of technology and modelling systems

The legal framework is crucial in ensuring success of projects, attracting the private sector, and ensuring economic growth. Risk management systems are also instrumental and should be put in place and abided by to ensure operational performance. This also encapsulates the shared authority dynamic of both sectors.

Continued use and growth of technology transfer and modelling systems is extremely important not only in PPP projects but also in the overarching construction industry. From the years 2013 to 2015, the percentage of contractors in the UK at a high level of BIM integration increased from 28% to 66%. At the same time construction gains increased by around 6% in 2014 and 8% in 2015 (Autodesk, 2015). Whereas the BIM adoption in UK has surpassed the 73% as per the BIM report 2020 (Graham, 2021). This statistic clearly illustrates the importance of continued use and investment in BIM to improve the profitability and economic sustainability of the industry. The profitability improvements caused by using BIM mostly include time saving methods. There are however BIM tools that can help save money in the earliest stages of a project's life. These include tools to accurately record and calculate budget and spending, this improves profitability as there will be fewer mistakes in documentation and the budget will be accurately laid out, thus removing the risk on overages later down the line and saving money (Landform surveys, 2021). There is a huge importance of using BIM in PPP projects in the UK. This is because in today's modern industry, there is a need for a great deal of information transfer and collaboration. BIM can aid in collaboration between sectors and influence the working relationship between the two. If the relationship is streamlined and the communication is efficient and accurate the overall operational performance of the project will be optimised (Haryati and Habib, 2018).

The availability of the current financial market is important in encouraging operational performance within PPP projects. If the financial market is in a good place, it acts as an incentive to the private sector to take an interest and invest into PPP projects (Akintoye et al., 2001b). One way to make the financial market accessible is to tie the finance provider into the consortium or SPV (special purpose vehicle) (Li et. al, 2005). An SPV is a legal entity whose purpose is to carry out a specific temporary task whilst separating itself from the original firm, thus isolating the firm from a large amount of financial risk (Gomez and Gambo, 2016). A steady and predictable financial market reduces risks for the private sector which further entices them to collaborate on large projects.

PPP Structure and Sustainability

In 1992, the then chancellor of the exchequer, Norman Lamont, announced the launch of the private finance initiative (PFI) (Allen, 2003). This set out a framework for a close relationship for the public and private sectors to collaborate on large government projects using the skills and finance from the private sector. The private sector was wary of the PFI scheme as it required a large capital investment up front and entailed a long and bureaucratic tendering process (Pretorius et al., 2008). Since the scheme was set up in a way to optimise collaboration, project performance, and to increase business profit for the private sector, it quickly became the priority in procuring NHS projects (Pollitt, 2002). The PFI scheme was continually optimised and improved, resulting in 780 projects recorded with a value of over £53 billion by the end of 2005 (Toms et al, 2009). Despite the PFI schemes success, it was drawing criticism by the late 2000's. this is due to the biased evidence used to argue in favour of the scheme (Pollock et al., 2007). The conclusion drawn by the criticism was that the PFI scheme was more expensive than it needed to be. The House of Commons (2011) drew the following conclusions:

- The use of PFI has the effect of increasing the cost of finance for public investments as the financing costs of PFI are typically 3-4% over that of government debt.
- In comparison to government's bond, the interest rate at that time was around 4%, compared to rates of around 8.5% on private borrowing.
- In the case PFI's inefficiency, for the same present value of finance-related payments, the government could have secured 71% more investment by borrowing on its own account.

As a result of these conclusions, it was decided that the PFI scheme could be further optimised to improve economic sustainability and operational performance of the projects being undertaken. Thus, the PF2 scheme was introduced in December 2012 (National audit office, 2018). The PF2 scheme was aimed at speeding up the tendering and procurement process while making the venture cheaper for the public and private sector. Under this scheme, the public sector would invest 10%-39% more equity into the project as to limit the amount being paid back to the private sector post construction. This way, the public sector becomes an equity stakeholder/ co investor, this minimises the conflict of interest from the private sector being investors and procurers (Haryati and Habib, 2018). Haryati and Habib (2018) Discussed a range of issues with the former PFI scheme and suggested a series of reforms adapted from HM Treasury (2012); and House of Commons (2014). These reforms include using public sector finance to invest in the projects, rather than borrowing from the private sector. The equity invested from the public sector allows for saving money through lower interest rates from the government. Another reform was also cut down substantially. The tendering process being cut down to a maximum of 18 months allows for not only the steady growth of projects but also attracts potential contractors who may have been discouraged by the lengthy process. Both factors influence social and economic sustainability by promoting growth and economic stability. The other reforms including transparency, flexibility, and accountability allows for a more amicable working relationship between the public and private sectors and promotes growth of future projects as well as improving overall operational performance of future projects.

Methodology

The data for this research was collected in a systematic manner utilising a questionnaire survey and then represented quantitatively as data on a spreadsheet. The information was gathered using a technique known as "snowball sampling." This method involves collecting information from a single participant, who then distributes the survey to others in his or her organisation or area of effect. This method is then repeated, exponentially growing the sample group over time. Because of the large number of potential responses from a small number of respondents contacted, this sampling strategy was used. This increases the likelihood of obtaining results from many people, hence boosting the data's quality and reliability. This sampling strategy also allows the survey to reach people you might not have otherwise been able to reach, such as large corporation directors and CEOs (Miller, 2003). This resulted in a more meaningful data collection, as well as added the ability to add experience to the potential respondents. The respondents were selected based on their previous job experience and present or previous sector of work. These responders were identified online, in places like LinkedIn, where a search for "construction manager" or "Construction Director" turned up a slew of industry insiders who could be easily contacted. Emailing several construction companies and requesting industry personnel to complete and, of course, pass on the survey was another option that was used.

The questionnaire survey was constructed to validate and investigate the themes and factors discussed in the literature review. This questionnaire aided in analysing the research topic by investigating the sustainability of the construction sector and linking it to the PPP structure. It also evaluated the critical success factors which ensure operational performance of the scheme. The questionnaire was constructed with demographic questions, and research specific questions. The questionnaire was split into categories: briefing, demographic, and research specific questions. The research specific questions were designed to be answered in a five-point Likert scale. This scale presented in Table 1 was used to quantify the answers given by the responses.

Table 1
Formulation of Questionnaire

Factor	Questions	Theme	Source(s)
Challenges to UK construction	14	Skilled worker shortage Time management issue Overrunning costs Cost management Technological advancements Productivity on site Cost affecting economic stability Reliance on importation Procurement issues caused by COV-19 and Brexit Waste and pollution issues not being improved	(Opoku and Ahmed, 2014); (Sarhan and Fox, 2012)
Drivers of PPP projects	7	Level of risk to environmental and economic sustainability Legal framework supporting PPP Support from current financial market The need for MMC & BIM in construction Communication between sectors Effectiveness of legislative requirements	(Doloi, 2012); (Robinson and Scott, 2009)
Operational performance of PPP projects	8	Effectiveness of voluntary agreements PF2 scheme improving risk management PF2 scheme improving sustainable practices PPP resolving fiscal issues Reduction of cost within construction projects Creating collaborative networks between sectors	(Yurdaku et al. 2022); (Chou and Pramudawardhani, 2015)

Results and Discussion

Analysis of Data

The research specific questions were split into sections. These are: Challenges to UK construction, performance of PPP projects, and Drivers of PPP projects. Each section was analysed separately as there are both limiting factors and success factors so, to gain a better understanding of the importance of each section and the questions within it. The RII of each question was used to analyse the importance and significance of each question and then was ranked based on its RII value. The RII was calculated by using the following equation.

$$RII = \frac{\mathrm{Ni1} \times 1 + \mathrm{Ni2} \times 2 + \mathrm{Ni3} \times 3 + \mathrm{Ni4} \times 4 + \mathrm{Ni5} \times 5}{(\mathrm{Ni1} + \mathrm{Ni2} + \mathrm{Ni3} + \mathrm{Ni4} + \mathrm{Ni5})\mathrm{A}}$$

where RII= Relative importance index for each question, Ni1= number of responses as “Strongly Disagree”, Ni2= number of responses as “Disagree”, Ni3= number of responses as “Neutral”, Ni4= number of responses as “Agree”, Ni5= number of responses as “Strongly Agree”, and A= highest weight of Likert scale (5 in this case). RII is an important tool to determine the relative significance of each question and to analyse the answers the participants have given. Khaleel and Nassar (2018) listed the following guidelines to determine the significance of the results depending on the RII value. 10.0 ≤ little significance ≤ 20.0, 20.0 ≤ some significance ≤ 40.0, 40.0 ≤ average significance ≤ 60.0, 60.0 ≤ high significance ≤ 80.0, and 80.0 ≤ very high significance ≤ 100.

Analysis of Challenges to UK Construction

Table 2 below shows the RII numbers of the questions asked in the category “challenges to UK construction”.

Table 2
RII values of Challenges to UK construction

Factor	1	2	3	4	5	RII	Category Rank
Challenges to UK construction						0.848168	
I believe that there is a shortage of skilled and experienced workers in construction	0	0	2	87	67	0.883333	5th
I believe that there are time management issues in the construction industry	0	0	3	56	97	0.920513	2nd
Construction projects often overrun	1	0	2	35	118	0.944872	1st
I believe that cost is not managed properly within construction projects	1	0	68	38	49	0.771795	12th
Costs often overruns in construction projects	0	0	4	120	32	0.835897	10th
I believe that construction projects struggle with productivity	0	2	3	53	98	0.916667	3rd
I believe that lack of technological advancements is a limiting factor in the construction industry	0	4	4	91	57	0.857692	7th
I believe that material costs create unstable economic patterns within construction projects	1	0	108	25	22	0.685897	14th
I believe that there is a large reliance on imported materials in construction	0	0	65	49	42	0.770513	13th
I believe that the UK has faced difficulties caused by covid-19 and Brexit with relation to procurement shortages	0	0	2	115	39	0.847436	8th
I believe that the above shortages will continue to affect the construction industry into the future	0	1	42	56	57	0.816667	10th
I believe that there are sustainability issues in the UK construction industry that are not being improved	0	2	18	79	57	0.844872	9th
I believe that there are waste management issues in the UK construction industry	0	0	2	76	78	0.897436	4th
I believe that there are water and air pollution issues in the UK construction industry	0	0	3	87	66	0.880769	6th

This section contains a very high average RII of 0.848168 overall, this means that the questions on average in this section have very high significance, revealing that the challenges presented in this section have a large significance in the construction industry in the UK. The question in this section with the highest RII was “Construction projects often overrun” with a RII of 0.944872. this shows that, it is the opinion of the experts questioned in this survey, that construction projects in the UK overrunning is a large problem and presents itself as a major challenge to the industry. This is backed up by the fact that “I believe that there are time management issues in the construction industry” had the second highest RII. This further reinforces the importance of the subject of time management and time overrunning. In contrast, the lowest scoring RII question was “I believe that material costs create unstable economic patterns within construction projects”. This shows that comparatively, cost fluctuation and economic stability is considered less important and a smaller challenge to UK construction, compared to time management. this can mean that it is more likely for a construction project to overrun on time however the material prices could fluctuate and cause cheaper procurement to aid in the overall project budget. The RII for this question was 0.685897. This represents a high level of significance notwithstanding the low rank. This shows that fluctuation of material price is still a challenge to the UK construction industry however it is a comparatively less important one in contrast to time and cost management. This research paper aims to investigate the success factors which ensure operational performance of PPP projects in the UK. Using the information from table 2 it is clear to see, that using proper time management can help in eliminating one of the most significant challenges to UK construction, thus boosting operational performance.

Analysis of Operational performance of PPP projects

Table 3 below investigates the factors involved in ensuring operational performance of PPP projects in the UK.

Table 3
RII values of Operational performance of PPP projects

Factor	1	2	3	4	5	RII	Category Rank
Operational performance of PPP projects						0.662981	
I believe that there are appropriate risk management frameworks in place in the public sector to mitigate economic and environmental risks	45	21	3	68	19	0.59359	5th
I believe that there are appropriate risk management frameworks in place in the private sector to mitigate economic and environmental risks	67	62	5	14	8	0.387179	8th
I believe that there is an appropriate legal framework to facilitate the operational performance of PPP projects	1	1	6	81	67	0.871795	4th
I believe that the current financial market facilitates operational performance of PPP projects	0	3	4	79	70	0.876923	3rd
I believe that there is a need for modern methods and techniques of construction (e.g., BIM, Lean, etc) and information sharing within the construction industry	0	2	2	79	73	0.885897	1st
I believe PPP leads to sufficient and	43	84	5	19	5	0.419231	6th

effective communication between sectors							
I believe that PPP legislative regulation has a positive impact on the construction industry in the context of sustainability	0	1	5	81	69	0.879487	2nd
I believe that PPP legislative regulation is widely accepted within the private sector	47	83	17	5	4	0.389744	7th

The overall RII for this section was 0.662981 showing that this section has high significance. The question with the highest significance was "I believe that there is a need for modern methods and techniques of construction (e.g., BIM, Lean, etc) and information sharing within the construction industry" with an RII of 0.885897 which means it has very high significance. The subject of MMC was covered in a previous section where it was discovered that MMC can boost the overall sustainability of the construction industry and it was discussed in the literature review how these methods can influence the sustainability of a project. This question highlights that the respondents believe that there is a need for MMC more specifically BIM, lean, and information sharing. This shows us that it is recognised that these methods can boost sustainability and operational performance and that there is a need for these methods in the industry. The question with the lowest RII in this section was "I believe that there are appropriate risk management frameworks in place in the private sector to mitigate economic and environmental risks" with an RII of 0.387179 meaning it has some significance. Compare this to the previous question "I believe that there are appropriate risk management frameworks in place in the public sector to mitigate economic and environmental risks" which had an RII of 0.59359 meaning it has average significance. It is clear to see that the respondents think that the risk management framework in the public sector is superior to the risk management framework in the private sector within the context of environmental and economic sustainability. This shows that the private sector could improve the overall operational performance and sustainability of PPP projects by improving its risk management frameworks to mitigate environmental and economic risks. Not only would this protect the private companies but also improve any given PPP projects' likelihood of success and performance.

Analysis of Drivers of PPP projects

Table 4 is named "drivers of PPP projects". This section was aimed at discovering the factors which drive PPP projects and ensure their performance.

Table 4
RII values of Drivers of PPP projects

Factor	1	2	3	4	5	RII	Category Rank
Drivers of PPP projects						0.791941	
I believe that voluntary agreements from the private sector improve environmental sustainability through PPP based sustainable construction projects	1	0	4	92	59	0.866667	2nd
I believe that voluntary agreements from the private sector improve economic sustainability through PPP based sustainable construction projects	0	2	2	98	54	0.861538	3rd
I believe that the use of the PF2 scheme has improved PPP projects in terms of risk management	1	0	7	91	57	0.860256	4th

I believe that the use of the PF2 scheme has improved PPP projects in terms of sustainability	1	0	6	119	30	0.826923	5th
I believe that the use of PPP projects aids in resolving fiscal issues within the public sector	1	1	8	69	77	0.882051	1st
I believe that the use of PPP projects helps reduce cost for both sectors	2	2	74	71	7	0.701282	6th
I believe that the use of PPP helps to create collaborative networks between private and public parties	1	77	51	18	9	0.544872	7th

The overall RII for this section was 0.791941 meaning this section has a high level of significance. The question with the highest RII was "I believe that the use of PPP projects aids in resolving fiscal issues within the public sector" with an RII of 0.882051 this factor is one with High significance. This shows that PPP projects can aid in the economic state and sustainability of the public sector and can promote economic growth by resolving fiscal issues. The 2nd highest RII was the question "I believe that voluntary agreements from the private sector improve environmental sustainability through PPP based sustainable construction projects" with the RII of 0.866667. This shows that not only does the PF2 scheme and PPP project philosophy aid in economic growth and sustainability, but it also helps promote environmental sustainability. The question in this section with the lowest RII number was "I believe that the use of PPP helps to create collaborative networks between private and public parties" with an RII value of 0.544872 which shows average significance. this result shows that the communication between the sectors when it comes to PPP projects is lacklustre. This can relate to some previous responses which highlight the need for MMC and BIM which could aid in creating creative networks and communication links between the public and private sectors. This is a critical success factor within the projects and should be improved to boost operational performance.

Conclusion

The research analysed the current practices and issues in the UK construction industry within the context of sustainability. This factor found large significance within utilising the skills and capital from the private sector to push for the implementation sustainable practices within projects. Another subject with substantial significance in this factor was the use of modern methods of construction to bolster and boost the current construction practices used today. The success factors of PPP projects were also split into 2 sections including operational performance of PPP and drivers of PPP. It was made clear that modern methods of construction are imperative within ensuring operational performance of these projects by utilising methods such as BIM and Lean construction. It was also found that the most significant factor which drives PPP projects is the resolution of fiscal and financial issues within the public sector. From this research it is possible to conclude that to ensure operational performance of PPP projects it is imperative to continue research and development of modern methods of construction as well as implementing BIM into the standard practices of the project. This can aid in the time, cost, and sustainable efficiency of a project and aid in promoting high quality work. It is also important to remember that at the heart of these projects there is a large focus on the financial benefit to the public and private sectors. The public sector must be able to resolve fiscal issues by continuing the project and the financial market must be accessible and stable to attract the skills and capital from the private sector.

References

Allen, G. (2003). The private finance initiative (PFI). House of Commons Research Paper 01/117.

Autodesk. (2015). “Building on BIM”. Available at: https://damassets.autodesk.net/content/dam/autodesk/www/campaigns/bim-constrction/fy15-aec-expand-construction-ebook-en-gb.pdf. Accessed: 10/03/2022

Azim, M., & Ahmed, H. (2015). Operational performance and profitability: an empirical study on the Bangladeshi ceramic companies. *International Journal of Entrepreneurship and Development Studies (IJEDS)*, *3*(1), 63-73.

Doloi, H. (2012). Understanding impacts of time and cost related construction risks on operational performance of PPP projects. *International Journal of Strategic Property Management*, *16*(3), 316-337.

Graham, D. (2021). The rise of BIM in the UK. BIMTODAY, January 7, 2021.

Haryati, S.N., & Habib, A. (2018). Critical success factors and contractual risks for private finance 2 (pf2) projects implementing building information modelling (BIM). School of the Built Environment, The University of Salford Salford, UK. PP.17-34.

HM Treasury. (2012). “A New Approach to Public Private Partnership.” Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/20511 2/pf2_infrastructure_new_approach_to_public_private_parnerships_051212.pdf. accessed: 20/03/2022

House of Commons. (2014). “Private Finance 2: Tenth Report of Session 2013-14. London: The Stationery Office Limited:.”. Available at: http://www.publications.parliament.uk/pa/cm201314/cmselect/cmtreasy/97/97.pdf. Accessed: 20/03/2022

Landform surveys (2021) ‘does BIM really save money on capital projects?’ available at: https://www.landform-surveys.co.uk/news/thoughts/bim-really-save-money-capital-projects/. Accessed: 10/03/2022

Li, B., Akintoye, A., Edwards, P.J., & Hardcastle, C. (2005). Critical success factors for PPP/PFI projects in the UK construction industry. *Construction management and economics*, *23*(5), 459-471.

Miller, R. (2003). Sampling, snowball: accessing hidden and hard-to-reach populations. The AZ of social research: A dictionary of key social science research concepts, 274.

National Audit office. (2018). “HM Treasury, PFI and PF2” Report by the Comptroller and Auditor General

Opoku, A., & Ahmed, V. (2014). Embracing sustainability practices in UK construction organizations: Challenges facing intra-organizational leadership. *Built Environment Project and Asset Management*, *4*(1), 90-107.

Pollitt, M.G. (2002). The declining role of the state in infrastructure investments in the UK. In S. V. Berg, M. G. Pollitt & M. Tsuji (Eds.), Private Initiatives in 312 Infrastructure: Priorities, Incentives and Performance (pp. 67-100). Glasgow: Edward Elgar Publishing.

Pollock, A.M., & Price, D. (2008). Has the NAO audited risk transfer in operational private finance initiative schemes? *Public Money and Management*, *28*(3), 173-178.

Pretorius, F., Chung-Hsu, B., Mclnnes, A., Lejot, P., & Arner, D. (2008). Project Finance for Construction and Infrastructure: Principles and Case Studies. Oxford, UK: Blackwell.

Robinson, H.S., & Scott, J. (2009). Service delivery and performance monitoring in PFI/PPP projects. *Construction management and economics*, *27*(2), 181-197.

Sarhan, S., & Fox, A. (2012). Trends and challenges to the development of a lean culture among UK construction organisations. In 20th Annual Conference of the International Group for Lean Construction, July 2009.

Toms, S., Asenova, D., & Beck, M. (2009). Refinancing and the Profitability of UK PFI Projects. In A. Akintoye & M. Beck (Eds.), Policy, Finance & Management for Public-Private Partnership (pp. 65-81). Oxford: Blackwell.

Yurdakul, H., Kamaşak, R., & Öztürk, T. Y. (2022). Macroeconomic drivers of Public Private Partnership (PPP) projects in low income and developing countries: A panel data analysis. *Borsa Istanbul Review*, *22*(1), 37-46

Communication Willingness Factors Between Project Stakeholders in the Construction Industry

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Effective communication is a critical component of project management and, as a result, an essential component of the construction business. Construction project teams present unique communication challenges with the multidisciplinary makeup of members that have different communication styles with varied levels of understanding, skills, and adaptability. Past research has been fragmented with understanding the factors that promote communication between contracting parties. This study identifies ten factors that impact communication willingness and tests the level of impact of each factor. Additionally, industry practitioners were surveyed on the factors impact on communicating with other project stakeholders. Fifty-three individuals were surveyed in the South-Central region of the United States, representing four different project stakeholders: owners, architects, project managers, and superintendents. A personal desire to succeed and communicating with skilled individuals were found to be the motivators that had the greatest impact on promoting communication willingness. One-way analysis of variance (ANOVA) was used to identify three differences with communication willingness between the different project stakeholders.

Key Words: Communication, Project Stakeholders, ANOVA

Introduction

Effective communication is a critical component of the construction business. Construction teams are generally reorganized and formed for almost every new project, creating the need to adapt quickly to new relationships. Scanlin (1998) noted that "ineffective communication is a root cause of most project failures." Proper communication is necessary to balance the asymmetry among project teams. Project managers and project team members spend approximately 90% of their working time engaged in some form of communication (Burke, 2010). Poor communication among stakeholders is the most common single item resulting in more time spent on a task than expected (Thomas et al., 2018). There is often a lack of communication willingness among project teams, which is not conducive to the realization of project success. (Wu et al., 2017). This paper explores motivators that impact the willingness to communicate among project team members, including the owners, architects, project managers, and superintendents.

Literature Review

DeSanctis and Monge (1998) defined communication as the process of sharing ideas, feelings and opinions between two or more people. Team communication is a two-way process through which project team members interact with one another (Orlikowski & Yates, 1994). Communication in construction projects is unique due to the nature of project teams: they are temporary in nature, have multiple stakeholders that don't stay on the project for its entire duration, and often have differing goals and responsibilities (Ibadov, 2015). Wu et al. (2017) defined communication among construction project teams as the process of information sharing, exchange, and transmission across the entire lifecycle of the project. Communication willingness, defined as the intention for a project team to share information (Ding et al., 2007), is an essential component of the communication process that can contribute towards project success. Wu et al. (2017) defined communication willingness as the extent to which the project team communicates and shares information with the other project teams participating in the project. Upon reviewing literature related to improving communication ten motivators were found to relate to communication willingness. They are presented in Table 1 and discussed below.

Table 1

Communication Willingness Factors

Factors	Short Description	Source
Intrinsic Motivation	A personal desire to succeed.	Murtagh, 2016
Extrinsic Motivation	Monetary rewards.	Murtagh, 2016
Contract Trust	Having a fully executed contract with agreeable terms with the individual.	Turner, 2007
Competence Trust	When the individual demonstrates high competence with their profession.	Turner, 2007; Turner, 2004
Emotional Trust	Having a good personal relationship with the individual.	Turner, 2004
Formal Communication	Using formal communication methods (e.g. emails, reports, written documents, etc.)	Johnson, 1994; Turner, 2004; Wu et al., 2017
Informal Communication	Using informal communication methods (e.g. oral communication, phone, text, etc.)	Johnson, 1994; Turner, 2004
Event Driven Communication Frequency	When we have identified project milestones in which we will communicate.	Turner, 2004
Calendar Driven Communication Frequency	When we have set weekly or monthly events in which we will communicate.	Turner, 2004
Leadership Driven Management	When the individual has good people skills.	Chan and Tse, 2003; Hagberg, 2006

Uncertainty, team conflict and the temporary nature of construction projects can all lead to decrease in willingness to communicate. However, there are several factors that should be considered that can lead to an increase in the desire to communicate. Communication willingness can be impacted by *intrinsic motivators*, such as a personal desire to succeed, and *extrinsic motivators*, such as monetary compensation. They serve as a driver towards the team members' desire to engage in the project. Intrinsic motivators come from within, and are flexible, with a longer lasting effect on individual team members (Murtagh et al., 2016). Extrinsic motivators are more controlled and driven externally in ways such as financial or profit related (Murtagh, 2016).

The need for trust is also an important factor that influences the project stakeholders' desire to communicate with their counterparts. Trust is the most important success factor in fostering cooperation (Cook and Hancher, 1990; Kwan and Ofori 2001; Cheung et al., 2007), eliminating adversarial relationships by information-sharing (Cook and Hancher, 1990), solving specific construction industry problems such as low productivity and growth rates (Kwan and Ofori, 2001), and establishing a sense of trustworthiness (Cheung et al., 2013). There are three types of trust that team members rely upon during the construction project: contract trust, competence trust and goodwill trust. (Turner & Muller, 2004; Fong & Lung, 2007; Hartman, 2000). *Contract trust* is the standard set by the agreement both parties enter. *Competence trust* is gained by a shared understanding that the professionalism, technical skills, and managerial style of the project team members will properly carry out the tasks of the project to achieve a successful outcome. *Emotional trust* is the ability to be able to get along with someone and work with them (Turner & Muller, 2004).

Both formal and informal communication methods can impact communication willingness and are needed in project team members relationships (Turner & Muller, 2004). Emails, memos and reports are examples of *formal communication*. They are critical requirements on construction projects. These types of formal communication should be used to communicate project updates and document project artifacts. While this form of communication is more time consuming, it is also more reliable. For example, the owner needs regular reassurance that the progress of the project is following a schedule that will ensure the project's completeness at a predefined time and cost. This requires the communication of analytical data. The owner needs to know that the PM understands the project requirements and is making decisions that are in the owner's best interest.

Informal communication is delivered verbally and is quicker and more personal than formal communication. Informal communication helps to develop trust needed among the project stakeholders, but when that trust is lost, the owner often tends to rely more on formal communication. Nevertheless, there should always be a follow up after informal communication to document the decisions made verbally. The combination of formal and informal communication will help instill a sense of confidence in the owner and avoid unmet expectations (Johnson, Donohue, Atkin & Johnson, 1994; Turner & Muller, 2004; Wu et al., 2017).

Frequency of communication among the project stakeholders can be divided into two different approaches: event driven or calendar driven (Turner & Muller, 2004). *Event driven communication* relies on project phases or milestones. *Calendar driven communication* occurs on a weekly, bi-weekly, or monthly basis. While many contractors focus their approach on monthly and milestone reporting, research shows that more frequent, less formal communication gives the owner the greatest comfort that they are being well informed (Turner & Muller, 2004). Good people skills are broadly applied to the management and leadership function of the project manager's and superintendent's positions and are considered to be *leadership driven management* (Hagberg & Strong, 2006).

Research Objectives and Methodology

In this study the ten communication willingness factors are measured to determine what motivates open and effective communication between construction project stakeholders. There are multiple stakeholders that are involved in any construction project; however, this study focuses on four of the common project team members: architects, owners, superintendents, and project managers. There were two main research questions in this study 1. Is there a difference in willingness to communicate among architects, owners, superintendents, and project managers based on the ten factors; 2. What are the most impactful factors that increase communication willingness among construction project stakeholders?

The data for this research was collected from surveys that were electronically distributed and collected to individuals in the construction industry. Survey participants from Texas and Oklahoma were invited to participate in the study. The survey included demographic questions and quantitative questions related to the ten factors. Each survey participant was asked to assess the level of agreement that each communication willingness factor improved communication with the other three stakeholder groups, using a 5 - point Likert scale with 1 being Strongly Disagree and 5 Being Strongly Agree.

To answer research question one, a one-way ANOVA was conducted to determine if there was a difference in willingness to communicate between project stakeholders based on each individual communication factor. A simple comparison of means was used to answer the second research question.

Data Analysis and Discussion

Fifty-three individuals participated in the survey: architects (n = 12), owners (n = 10), superintendents (n = 14), and project managers (n = 17). Survey respondents varied in the length of work experience, gender, and average project length. One limitation was observed while analyzing the study results. The study had an unequal number of cases (responses by the Architect, Owner, Superintendent, and Project Manager participant groups) in each group. Because sample sizes were not the same in all groups, there was a concern with having an unbalanced design. Although realizing that this is a limitation of the study, the effect of potential unbalanced design was hard to mitigate considering the lack of control over participant responses.

Communication Willingness Factors Impact

A simple comparison of means was used to identify the most impactful communication willingness factors. *Intrinsic Motivation* or the personal desire to succeed was rated the highest among the four stakeholders (4.62). Individual competence within their profession or *Competence Trust* was the second most important factor (4.43) that increases willingness to communicate with the architect, emphasizing the importance of architect's professional experience. Table 2 presents the means from the four stakeholders. The factors are ordered in the ranking of the overall averages of the stakeholders.

Table 2

Ranked Order of Communication Willingness Factors

Factors	Arch. (Avg)	Owner (Avg)	Supt. (Avg)	PM (Avg)	Overall (Avg)
Intrinsic Motivation	4.56	4.68	4.64	4.60	4.62
Competence Trust	4.64	4.13	4.54	4.42	4.43
Emotional Trust	4.21	4.48	4.35	4.31	4.34
Calendar Driven Communication Frequency	4.26	4.25	4.28	4.21	4.25
Leadership Driven Management	4.22	4.32	4.25	4.13	4.23
Event Driven Communication Frequency	4.11	4.10	3.91	4.08	4.05
Formal Communication	4.09	4.02	3.67	4.18	3.99
Contract Trust	4.07	4.00	3.66	3.96	3.92
Informal Communication	3.89	3.81	3.87	3.96	3.88
Extrinsic Motivation	3.21	3.38	3.18	3.12	3.22

Differences with Communication Willingness

A one-way ANOVA was conducted to test if there were differences with the communication willingness factors among architects, owners, superintendents, and project managers. Overall, forty ANOVAs were run with a significance level (Alpha) of 0.05. Only three tests identified differences between the stakeholders' responses.

Contract Trust Impact with Communication with the Architect

A significant difference was found in the project stakeholders' willingness to communicate openly with the Architect based on having a fully executed contract. The difference was found to be statistically significantly different for the Owner, Superintendent, and Project Manager groups, $F(2, 38) = 3.582$, $p = .0375$, presented in Table 3.

TABLE 3:

ANOVA - Contract Trust Impact with Communication with the Architect

SUMMARY						
Groups	***Count***	***Sum***	***Average***	***Variance***		
Owner	10	42	4.2	0.4		
Supt	14	61	4.357143	0.401099		
PM	17	62	3.647059	0.867647		
ANOVA						
Source of Variation	***SS***	***df***	***MS***	***F***	***P-value***	***F crit***
Between Groups	4.278971	2	2.139486	3.582048	0.037568	3.244818

Within Groups	22.69664	38	0.59728
Total	26.97561	40	

Project Managers rated this factor lower than both owners and superintendents. Depending on the delivery method, project managers will not have contractual agreements with the architect, which explains the lower rating. However, a difference was found between the Superintendent and the PM which typically work for the construction company. Because the PM is typically more involved with the project contracts, this could demonstrate that the superintendents are not as aware of the contractual obligations between the parties.

Competence Trust Impact with Communication with the Superintendent

A significant difference was found on the project stakeholders' willingness to communicate openly with the Superintendent based on *Competence Trust*. The difference was found to be statistically significantly different for the Architect, Owner, and Project Manager groups, $F(2, 36) = 4.578$, $p = .0169$, presented in Table 4.

TABLE 4

ANOVA - Competence Trust Impact with Communication with the Superintendent

SUMMARY						
Groups	***Count***	***Sum***	***Average***	***Variance***		
Arch	12	49	4.083333	0.810606		
Owner	10	49	4.9	0.1		
PM	17	79	4.647059	0.367647		
ANOVA						
Source of Variation	***SS***	***df***	***MS***	***F***	***P-value***	***F crit***
Between Groups	3.993288	2	1.996644	4.578578	0.016919	3.259446
Within Groups	15.69902	36	0.436084			
Total	19.69231	38				

Although still high, the Architect placed less value in the competence trust with the superintendent than the Owner and Project Manager. Both the Owner and the Project Manger treated professional competence as a significant factor in their desire to communicate with the Superintendent. Because the majority of the Architects communication with the contractor is typically with the PM could be the reason that explains why the Architects rated contractual trust with the Superintendents lower.

Informal Communication Impact with Communication with the Project Manager

A significant difference was found on the project stakeholders' willingness to communicate openly with the Project Manager based on *Informal Communication*. The difference was found to be statistically significantly different for the Architect, Owner, and Superintendent groups, $F(2, 33) = 3.533$, $p = .0407$, presented in Table 5.

TABLE 5

ANOVA - Informal Communication Impact with Communication with the PM

SUMMARY						
Groups	***Count***	***Sum***	***Average***	***Variance***		
Arch	12	42	3.5	0.636364		
Owner	10	43	4.3	0.455556		
Supt	14	57	4.071429	0.532967		
ANOVA						
Source of Variation	***SS***	***df***	***MS***	***F***	***P-value***	***F crit***
Between Groups	3.860317	2	1.930159	3.533016	0.040707	3.284918
Within Groups	18.02857	33	0.54632			
Total	21.88889	35				

The Owner treated *Informal Communication* as a more important factor than the Architect in their desire to communicate with the Project Manager. The Owner has a higher preference for *Informal Communication*, which includes face to face conversations, phone calls, text messages, etc. than the Architect. This could be the result of the issues seen in project delivery methods such as Design-Bid-Build that has put the Architects and the Contractors interests in an adversarial relationship. Formal communication becomes critical in disputes, which results in the Architect and the Contractor relying more on formal communication that supports their efforts during project disputes. Architects rated this factor as the ninth most impactful factor for increasing communication willingness. Additional research could focus on the Architects lower value with communicating informally and the impact on relationships between stakeholders.

Conclusion

This paper has explored the communication motivators that impact communication willingness among project stakeholders. Communication willingness is defined as the extent to which the project team communicates and shares information with the other project teams participating in the project (Wu et al., 2017). Ten factors were identified from past research that impact an individual's willingness to communicate effectively, presented in Table 1. Fifty-three professionals in the South-Central region of the United States participated with the study, representing four of the common project stakeholders: architects, project managers, owners, and superintendents. The objective of the study was to identify what are the most influential factors for an individual to be willing to communicate and to identify if there were any differences among the four stakeholders' communication methods.

Based on the overall data analysis, there was a high level of agreement among the groups with the factors' influence on communication willingness. A personal desire to succeed was the most influential factor for communication willingness. Communicating with individuals that demonstrate high competence was the second most influential factor on communication willingness. Interestingly, monetary rewards ranked as the least important factor for all project stakeholders.

Forty ANOVA tests were conducted with the communication willingness factors to identify differences within the four groups of stakeholders. Three statistically significant differences were identified:

- Compared to Owners and Superintendents, PMs rated *Contract Trust* lower with regards to communicating with Architects.
- Compared to Owners and PMs, Architects rated *Competence Trust* lower with regards to communicating with Superintendents.
- Compared to Owners and Superintendents, Architects rated *Informal Communication* lower with regards to communicating with Project Managers.

The findings demonstrated high level of agreement of the factors influence. However, the three difference identified above demonstrate that the contractual relationships between the parties have an impact on communication. The level of impact can be tested in the future. Additionally, future research can focus on how the different delivery methods impact communication willingness and how the impact of the factors changes throughout the project timeline. Limitations of the study include the small sample size, which could be expanded upon in the future for further validation.

References

Burke, R. 2010. *Fundamentals of project management: Tools and techniques*. Ringwood: Burke Publishing.

Cheung, S. O., and Wong, P. S. P., 2007. *Trust in co-operative contracting in construction*. Hong Kong Press. 147 – 170.

Cheung, S., Yiu, T., and Lam, M. 2013. Interweaving Trust and Communication with Project Performance. *Journal of Construction Engineering and Management*, 139(8), 941-950.

Cook, L and Hancher, D.E. (1990). Partnering Contracting for the Future, *Journal of Management in Engineering.*

Desanctis, G., and Monge, P. 1998. Communication Processes for Virtual Organizations. *Journal of Computer – Mediated Communication*, 3(4), 0-0.

Ding, Z., Ng, F., and Cai, Q. 2007. Personal constructs affecting interpersonal trust and willingness to share knowledge between architects in project design teams. *Construction Management and Economics*, 25, 937–950.

Fong, P. S. W., and Lung, B. W.C. 2007. Interorganizational teamwork in the construction industry. *Journal of Construction Engineering and Management*, 133(2), 157-168.

Hagberg, N. and Strong, K. 2006. Key Attributes for Successful Leadership in Construction: Project Managers and Superintendents, Retrieved from: https://lib.dr.iastate.edu/cgi/viewcontent.cgi?article=1897&context=rtd.

Hartman F. T. 2000. *Don't park your brain outside*. Project Management Institute.

Ibadov, N. 2015. Fuzzy Estimation of Activities Duration in Construction Projects. *Archives of Civil Engineering*. 62(2), 23 – 34.

Johnson, J., Donohue, W., Atkin, C., and Johnson, S. 1994. Differences between formal and informal communication channels. *The Journal of Business Communication*, 31(2), 111.

Kwan, A. Y. and Ofori, G. 2001. Chinese culture and successful implementation of partnering in Singapore's construction industry. *Construction Management in Economics*. 19(6), 619 – 632.

Murtagh, N., Roberts, A., and Hind, R. 2016. The relationship between motivations of architectural designers and environmentally sustainable construction design. *Construction Management and Economics*, 34(1), 61-75.

Orlikowski, W. and Yates, J. 1994. Genre Repertoire: The Structuring of Communication Practices in Organizations. *Administrative Science Quarterly*, 39(4), 541.

Scanlin, J. (1998). "The Internet as an enabler of the Bell Atlantic project office." *Proj. Manage. J.*, 9(2), 6–7.

Thomas, E., Schott, P., Bowman, J., Snyder, J., & Spare, N. 2018. 2018 Industry Report Construction Deconstructed, PlanGrid. (online). Retrieved from https://www.plangrid.com/ebook/construction-disconnected/

Turner, J. R. and Müller, R. 2004. Communication and Co-operation on Projects Between the Project Owner As Principal and the Project Manager as Agent. *European Management Journal*, 22(3), 327-336.

Wu, G., Cong, L., Zhao, X. and Zuo, J. 2017. Investigating the Relationship between Communication-Conflict Interaction and Project Success among Construction Project Teams. *International Journal of Project Management*, 35(8), 1466 – 1482.

A Safe Collection Process of Covid-19 Disposable Face Masks for the Applications in Asphalt Pavements

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During the Covid-19 pandemic, plastic pollution became exacerbated by the disposal of face masks. The practical collection, processing, and application of the face mask have become a major challenge. Several studies have examined the added benefits of using face masks on asphalt pavements; however, these studies were limited to the application and have not addressed the appropriate collection process. This research aims to develop a theoretical collection process of disposable face masks originating from locations other than hospitals. The process aims to collect face masks safely and practically from residential, commercial, and educational zones. The masks would be collected twice a month and disinfected and sterilized before being transported to a shredding company for processing before being transported to an asphalt plant for use in asphalt mixtures. The developed collection method will minimize the risk of being affected by the Covid-19 virus and provide a practical procedure that can be used by waste management facilities. Additionally, the developed collection method could aid the construction industry in adopting a more environmentally friendly, sustainable, and cost-effective method of construction.

Key Words: Plastic Waste, Construction, Construction Material, Recycling, Safety, Sustainability, Environment, Covid-19, Face mask, Waste Collection

Introduction

The whole world is facing the problem of the Covid-19 pandemic. There are millions of people who have lost their lives due to getting unconscious while wearing Personal Protection Equipment (PPE) (e.g., masks, shields, or gloves) (De, 2020; Saberian et. al., 2021). The use of face masks as part of the health campaign against the coronavirus has been so successful that it has become a necessity to prevent the spread of the virus (Zhou et al., 2022; Iboi et al., 2021; Hornik et al., 2020; Royo-Bordonada et al., 2020). Though the use of face masks is incredibly needed, disposing of them is threatening the environment. Daily, a large amount of waste is generated from the disposable of millions of masks. In 2020, the total estimated used face masks were more than 129 billion globally. A sharp 20% growth is expected between 2020 and 2025 (Akarsu et al., 2021; Fernández-Arribas et al., 2021; Prata et. al., 2020). The collection of face masks is a very challenging task because they can be easily littered in many places (Prata et. al., 2020; Saberian et. al., 2021) without breaking down in the environment (Pandit et al., 2021; Morganti, 2020; Dhawan et al., 2019; Henneberry, 2020), which results in major waste management and environmental issues (Aragaw, 2020). According to Bai & Sutanto (2002), recycling is the most widely accepted sustainable method of plastic waste management. Nevertheless, recycling plastic wastes is a multifaceted process that involves collection, processing, storage, transportation, treatment, and application. Waste collection and transportation account for about 70% of the recycling process cost (Greco et al., 2015; Tavares et al., 2009). Therefore, a proper collection method is essential to determine the most cost-effective recycling process (Huang et al., 2011; Jacobsen et al., 2013). While the use of plastic waste and other waste by-product (i.e., steel slag) as a modifier in asphalt pavement has greatly enhanced the road's adhesion, lowered the thermal susceptibility of pavements, improved asphalt performance, and reduced construction costs (Rahat et al., 2022a; Rahat et al., 2022b; Wang et al., 2022), more work is still needed on developing as safe and practical collection process. This paper aims to develop a theoretical collection process of disposable face masks that is originated from locations other than hospitals. Residential, commercial, and educational zones are used as focused collection areas. Since medical plastic wastes are incinerated and present potential bio-medical hazards (Tejaswini et al., 2022; Chowdhury et al., 2022), they are not considered in this study. The masks would be collected twice a month with the application of disinfectants and sterilization procedures and transported to a shredding company for processing before transporting them to the asphalt plant for application in asphalt mixtures. The developed process will minimize the risk of being affected by Covid-19 virus and aid the construction industry in adopting a more environmentally friendly, sustainable, and cost-effective method of construction.

Literature Review

Applications of Covid-19 Plastic Wastes in Construction Application

During the pandemic of the Covid-19 personal protective equipment (PPE) (i.e., face mask, face shield, gloves) has become popular among the people. For this reason, the amount of used PPE, especially face masks have been increased drastically, and for the unawareness of people face masks are found here and there. Since PPE can save people from Covid-19, it will have a bad long-term impact on the environment as most of the PPEs are made with non-biodegradable material. The disposable face mask is the most used and is made of polypropylene (Henneberry, 2020). As per the best knowledge of the author, there are several studies has been conducted with used Covid-19 PPE (i.e., face masks, face shield, gloves) for construction application (e.g., pavement base/subbase, hot mix asphalt (HMA), concrete). The authors found the improvement of mechanical performance of the structures by using this PPE in construction. Table 1 provides a review of the most relevant studies on Covid-19 PPE used in construction applications.

Table 1

Studies on the application of used Covid-19 PPE in construction

Author	PPE	Application	Tests conducted	Results
Saberian et al., (2021)	Face mask	Pavement base/subbase	Modified compaction test Unconfined compressive strength Resilient modulus (Mr)	Improved compressive strength Improved resilient modulus
Kilmartin-Lynch et al., (2021)	Face mask	Concrete	Compressive strength Indirect tensile strength Elasticity modulus Ultrasonic pulse velocity	Improved overall concrete quality
Wang et al., (2022)	Face mask	HMA	Superpave mix design Asphalt pavement analyzer test (APA)	Improved rutting depth

Goli & Sadeghi, (2022)	Face mask	HMA	Marshall test Resilient modulus Indirect tensile Moisture damage Rutting and Fatigue test	Improved the overall properties of HMA
Kilmartin-Lynch et al., (2022a)	Nitrile gloves	Concrete	Compressive strength Modulus of elasticity Ultrasonic pulse velocity Scanning Electron Microscope (SEM)	Improved compressive strength Improved bond strength in microscale
Kilmartin-Lynch et al., (2022b)	Isolation gown	Concrete	Ultrasonic pulse velocity (UPV) Compressive strength Flexural strength test Scanning Electron Microscope (SEM)	Improved mechanical properties of concrete
Massarra et al., (2022)	Face mask	HMA	Cost estimation Life cycle cost analysis (LCCA)	Improved LCCA

Using shredded face mask blends at different percentages for highway base and subbase applications, Saberian et al., (2021) tested modified compaction and resilient modulus. Recycling concrete aggregate base and three different concentrations of shredded face mask (1%, 2%, and 3%) were combined for stiffness and strength. Fibrous recycled concrete aggregate mixes strengthened, and pliability increased with the addition of shredded face mask fibers. Strength remained at 216 kPa with 1% SFM and RCA added, but modulus increased (314.35 MP).

Based on this trend, Kilmartin-Lynch et al., (2021) tested concrete with a face mask. For pressure strength and indirect tensile strength, elasticity modulus, and ultrasonic pulse velocity, the masks were inserted with volumes of 0% (control), 0.10%, 0.15%, 0.20%, and 0.25%. Concrete settings improved in strength and quality as a result of the addition of single-use masks.

In 2022, Wang et al. evaluated the rutting resistance of hot mix asphalt (HMA) pavement using the Covid-19 face mask for the first time. By adding 1.5% of shredded face mask (SFM) by weight to the mix, the rutting depth was reduced to 0.93 mm, nearly nil.

Goli & Sadeghi, (2022) followed up on this study by incorporating two different sizes of SFMs into a mix of HMA, one which was 8 mm length and one which was 12 mm in length. In order to evaluate the overall properties of the HMA, the researchers conducted the Marshall test, resilient modulus, indirect tensile, moisture damage, rutting, and fatigue test for both scenarios. It has been found that in both scenarios, there has been an improvement in the overall quality of the HMA, although the improvement in the 12 mm fiber mixture has shown better performance than the 8 mm fiber mixture.

In line with the trend toward face masks, Kilmartin-Lynch et al. (2022a) used shredded nitrile gloves when performing structural concrete work. In order to determine the effect of shredded nitrile gloves on concrete's mechanical properties, quality, and bond performance with cement matrix, compression strength, modulus of elasticity, ultrasonic pulse velocity, and SEM-EDS analysis were conducted. Blended concrete composites with 0.2% shredded nitrile gloves show a 22% increase in compressive strength after 28 days. The compressive strength of nitrile gloves is improved by 20% after 28 days when they are shredded by 0.3%. The interfacial transition zone (ITZ) of the nitrile rubber and cement matrix shows no gaps after 28 days when they are shredded by 0.3%.

Furthermore, Kilmartin-Lynch et al., (2022b) used plastic-based isolation gowns for structural concrete. As part of the concrete mix, the shredded isolation gowns were added at 0.01%, 0.02%, and 0.03%. A series of experiments was conducted alongside an SEM-EDS analysis to study the effects of various concentrations of shredded isolation gowns on the concrete's mechanical properties. Based on the results, the bridging effect was enhanced between the cement matrix and shredded isolation gowns, resulting in increased compressive strength, flexural strength, and modulus of elasticity.

Finally, Massarra et al., (2022) estimated the cost of construction of Covid-19 mask-modified asphalt pavement and conducted a life cycle cost analysis (LCCA) of mask-modified asphalt pavement and conventional asphalt pavement. Even though mask modified asphalt pavements have higher up-front costs, LCCA showed a 29% reduction in maintenance costs over its full 40-year lifespan.

Although previous studies have shown that using face masks improves asphalt performance, and is environmentally beneficial and cost-effective, the major challenge is collecting, separating, and processing the masks. There are no available safety procedures for collecting face masks from sources other than hospitals and then transferring the collected masks to the casting field so they can be used in asphalt mixtures.

Methodology

Developing a Collection Process of Disposable Face Masks

In this section, a theoretical process for collecting face masks from sources other than hospitals is developed. It should be noted that no practical application has been conducted. Usually, the medical masks from hospitals are collected in separate bags and then incinerated (Gidarakos et al., 2009). For this reason, the potential sources of disposable masks will be residential buildings, and commercial and educational districts. Figure 1 illustrates the steps of the collection process. Residential, commercial, and educational zones will be a focused area for collection. The collection sites will be designated by the solid waste management facility. Ciaccia, 2020 found that the presence of the Covid-19 virus in masks would not exceed seven (7) days. Therefore, to prevent the spread of the Covid-19 virus during collection, disposable face masks will be collected twice a month and a total cycle of 6 weeks from setting up to retrieving. All the containers will be setup at the starting of the procedure by the solid waste management facility and labeled with week and days where the week of setting up will be considered as Week 1. Containers of Weeks 1 and 2 will be collected in Week 4 and containers of Weeks 3 and 4 will be collected in Week 2 of the following month and the cycle continued.

After collection from the sites, the masks will be transported to the recycling center for sterilization and separation. Disinfectants and sterilization procedures must be used for disinfecting the face masks. Some common practices suggested by Kampf et al., (2020) are 62–71% ethanol, 0.5% hydrogen peroxide, or 0.1% sodium hypochlorite within 1 min of subjection to the masks. Other applied dry heat technology on the masks at 70°C for one hour (Xiang et al., 2020). Because of its easy application and low cost, 0.5% hydrogen peroxide concertation for a minimum exposure time of 1 minute will be used.
The shredding company will be contacted earlier, so the sanitized masks are picked up either on the same day or the next day of sanitization. The masks will then be transported to a shredding company for removal of ear loops and nose strips and shredding. Finally, the shredded disposable face masks will be transported to the casting yard to prepare modified hot mix asphalt (HMA) samples to perform laboratory tests to evaluate the mechanical performance of disposable face masks modified HMA samples.

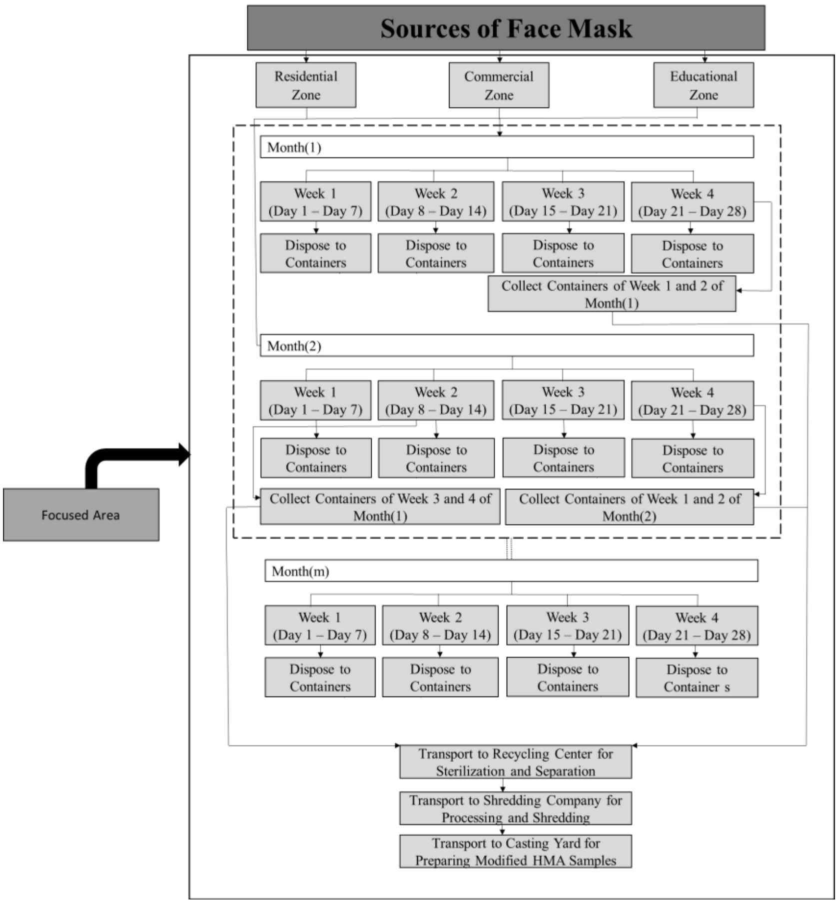

Figure 1. Collection process of disposable face masks

To carry out the collection, sterilization, and separation of face masks several numbers of laborers will be required. The number of labor depends on the number of collection points, containers, and volume of face masks.

Discussion

Example of Collection Process of Disposable Face Mask

Due to lack of accessibly to collection points because of Covid-19, the actual collection was not carried out, instead example of an application was carried out. It should be mentioned that this example does not represent any actual work. For this example, three collection points, four large containers of 95 gal (Capacity of 0.40 Tons of masks) at each location (i.e.,12 containers in total), and an arbitrary date (February 1st) would be chosen. The 12 containers would be assumed to be set up on February 1st, in the three collection points designated by the solid waste management agency and labeled with the week and days as follows: (Feb 1- Feb- 7), (Feb 8- Feb 14), (Feb 15- Feb 21), (Feb 22- Feb 28). Containers of Weeks 1 and 2 labeled as (Feb 1- Feb- 7), (Feb 8- Feb 14), and Weeks 3 and 4 labeled as (Feb 15- Feb 21), (Feb 21- Feb 28), would be collected on February 28th, and March 14th, respectively at the three collection points and transported to the recycling center of the solid waste management agency for separation and sanitization. Figure 4.1 shows the steps that would be taken only for one collection point. The same steps should be followed for the other two collection points.

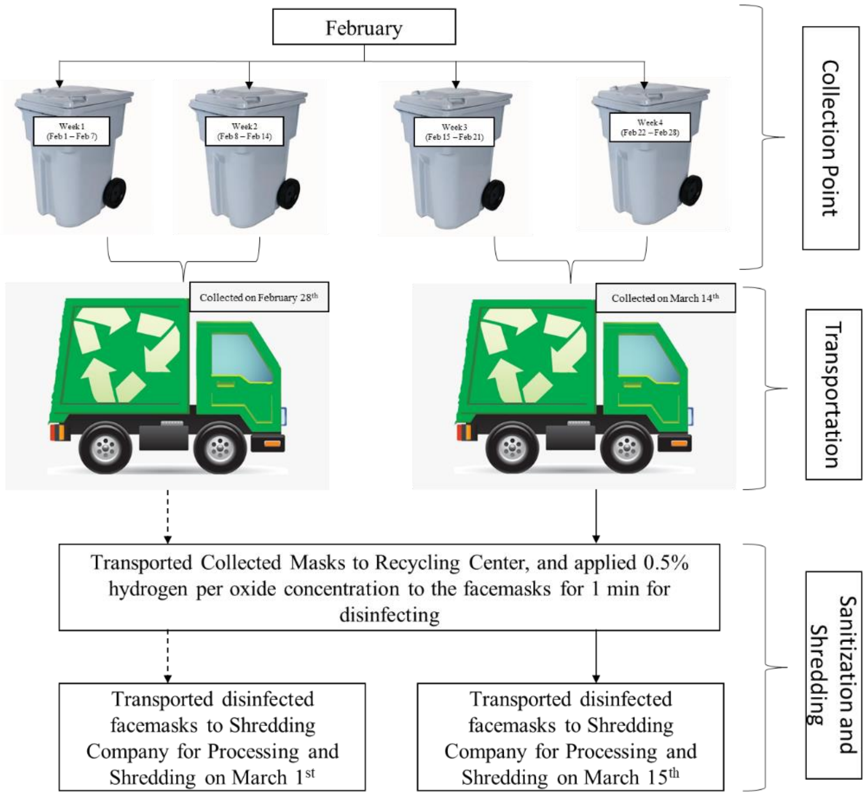

Figure 2. Flow chart of the example application at collection point

For sanitization, one bottle (32 oz) of hydrogen peroxide (H_2O_2) with 0.5% concentration applied for 1min would be needed for each container. Each container would take an average of 1 hour to set up, pick and sanitize. The shredding company would be contacted, and the pickup date would be scheduled on the second day of sanitization. The disinfected masks of containers of Weeks 1 and 2 labeled as (Feb 1- Feb- 7), (Feb 8- Feb 14), and Weeks 3 and 4 labeled as (Feb 15- Feb 21), (Feb 21- Feb 28), would be picked up on March 1st and March 15th, respectively. No labor would be needed for shredding since the shredding company offered a package that includes the pickup from the recycling center, removal of ear loops and nose strips, shredding of the face masks, and transportation to the casting yard. Based on the proposed methodology, Massarra et al. (2022) estimated the total cost associated with the application of face mask in HMA pavement as three-part costs: Cost of face mask collection, cost of face mask processing (i.e., shredding), and cost of HMA materials preparation with plastic.

Table 2 shows the total pavement structure cost with and without face masks for different pavement sections adopted from (Massarra et al, 2022).

Table 2

Total pavement structure cost with and without face masks for different pavement sections for one lane asphalt pavement (Massarra et al, 2022)

Length(m)	Total cost of mask collection	Total cost of mask processing	Total cost of asphalt preparation	Total cost masks	Total cost without masks

1000	$1,311	$1779	$37,238	$37,754	$37,238
500	$655	$889	$18,576	$18,920	$18,576
250	$328	$445	$9,460	$10,074	$9,460
100	$131	$178	3,698	$3,784	3,698

There are three costs associated with the application of face masks to HMA pavement: the cost of collecting face masks, the cost of processing them (i.e., shredding), and the cost of preparing HMA materials with recycled plastic. There are several costs involved in collecting face masks, including the cost of setting up and picking up containers, sorting, and sanitizing masks, the cost of transportation to and from the waste facility, and the market price of the containers. Among the costs involved in processing face masks are those associated with transportation from the waste management facility to the plastic processing plant, the plastic processing plant to the asphalt mixing plant, as well as the cost of processing the recycled plastics. For HMA preparation with a mask, the cost will vary depending on the total weight of asphalt mixture and face mask modifier required for pavement sections, as well as the unit price for HMA, which will vary from location to location. Generally, agencies conducting the practical application on using face masks for asphalt pavement will be responsible for the collection, processing, and application costs. Despite the initial costs paid by these agencies it was found that there is a 29% maintenance cost reduction over the 40 years life cycle of the asphalt pavement when using facemasks (Massarra et al., 2022).

Conclusions and Recommendations

Globally, due to the wide spread of the Covid-19 pandemic, a large amount of plastic waste has been generated. Using Covid-19 plastic waste in various construction applications can improve environmental sustainability, reduce construction costs, improve performance, and provide construction materials at a consistent rate. The collection process of single-used Covid-19 face masks has been developed in this study.

We have no intention to generalize the results and conclusions. Therefore, more in-depth work is needed on the application of the proposed methodology presented in this study. We want to mention that during the time of this study, Covid-19 was at its peak and there was high restriction of collecting Covid-19 generated wastes by any individuals or organizations except solid waste management agency. Although there was no practical application, the authors made sure to consult with the solid waste management agency to get their insight on the theory and found that the proposed methodology is in alignment with the process adopted by the solid waste management agency. The study concluded and recommended the following:

- Possibility to collect face masks without contracting Covid-19 following the collection process developed in this study.
- Same collection process can also be applied to other plastic wastes.
- Findings provide valuable insights into future efforts by industry and government agencies to develop sustainable approaches for the transportation, energy, and environmental industries.
- The research could provide a solution to reduce the plastic waste that is polluting the environment due to Covid-19 or another pandemic
- Research is required to develop a safe collection process for medical-generated plastic waste.
- A practical application is required to justify the feasibility of the process.

References

Akarsu, C., Madenli, Ö., & Deveci, E. Ü. (2021). Characterization of littered face masks in the southeastern part of Turkey. *Environmental Science and Pollution Research*, *28*(34), 47517–47527. https://doi.org/10.1007/s11356-021-14099-8

Aragaw, T. A. (2020). Surgical face masks as a potential source for microplastic pollution in the covid-19 scenario. *Marine Pollution Bulletin*, *159*, 111517. https://doi.org/10.1016/j.marpolbul.2020.111517

Bai, R., & Sutanto, M. (2002). The practice and challenges of Solid Waste Management in Singapore. *Waste Management*, *22*(5), 557–567. https://doi.org/10.1016/s0956-053x(02)00014-4

Chowdhury, T., Chowdhury, H., Rahman, M. S., Hossain, N., Ahmed, A., & Sait, S. M. (2022). Estimation of the healthcare waste generation during COVID-19 pandemic in Bangladesh. *Science of The Total Environment*, 811, 152295. https://doi.org/10.1016/j.scitotenv.2021.152295

Ciaccia, C. (2020, April 8). Coronavirus can live on surgical masks for 7 days, but 'standard disinfection methods' can kill it: Study. *The Fox News*. Retrieved October 26, 2021, from https://www.foxnews.com/science/coronavirus-on-surgical-mask-7-days

Dhawan, R., Bisht, B. M., Kumar, R., Kumari, S., & Dhawan, S. K. (2019). Recycling of plastic waste into tiles with reduced flammability and improved tensile strength. *Process Safety and Environmental Protection, 124, 299–307*. https://doi.org/10.1016/j.psep.2019.02.018

De, S. (2020). Impacts of the COVID-19 pandemic on Global Education. *COVID-19 Pandemic Update 2020*, 84–94. https://doi.org/10.26524/royal.37.6

Fernández-Arribas, J., Moreno, T., Bartrolí, R., & Eljarrat, E. (2021). Covid-19 face masks: A new source of human and environmental exposure to organophosphate esters. *Environment International*, *154*, 106654. https://doi.org/10.1016/j.envint.2021.106654

Goli, A., & Sadeghi, P. (2022). Evaluation on the use of COVID-19 single-use face masks to improve the properties of Hot Mix Asphalt. *Road Materials and Pavement Design*, 1–18. https://doi.org/10.1080/14680629.2022.2072376

Gidarakos, E., Petrantonaki, M., Anastasiadou, K., & Schramm, K.-W. (2009). Characterization and hazard evaluation of bottom ash produced from Incinerated Hospital Waste. *Journal of Hazardous Materials*, *172*(2-3), 935–942. https://doi.org/10.1016/j.jhazmat.2009.07.080

Greco, G., Allegrini, M., Del Lungo, C., Gori Savellini, P., & Gabellini, L. (2015). Drivers of solid waste collection costs. empirical evidence from Italy. *Journal of Cleaner Production*, 106, 364–371. https://doi.org/10.1016/j.jclepro.2014.07.011

Henneberry, B. (2020). How Surgical Masks are Made, Tested and Used., Tested and Used. *https://www.thomasnet.com/articles/other/how-surgical-masks-are-made/*.

Huang, Y.-T., Pan, T.-C., & Kao, J.-J. (2011). Performance Assessment for Municipal Solid Waste Collection in Taiwan. *Journal of Environmental Management*, *92*(4), 1277–1283. https://doi.org/10.1016/j.jenvman.2010.12.002

Hornik, R., Kikut, A., Jesch, E., Woko, C., Siegel, L., & Kim, K. (2020). Association of covid-19 misinformation with face mask wearing and social distancing in a nationally representative us sample. https://doi.org/10.31234/osf.io/k8pds

Iboi, E., Richardson, A., Ruffin, R., Ingram, D. A., Clark, J., Hawkins, J., McKinney, M., Horne, N., Ponder, R., Denton, Z., Agusto, F. B., Oduro, B., & Akinyemi, L. (2021). Impact of public health education program on the novel coronavirus outbreak in the United States. *Frontiers in Public Health*, *9*. https://doi.org/10.3389/fpubh.2021.630974

Jacobsen, R., Buysse, J., & Gellynck, X. (2013). Cost comparison between private and public collection of residual household waste: Multiple case studies in the Flemish Region of Belgium. *Waste Management*, *33*(1), 3–11. https://doi.org/10.1016/j.wasman.2012.08.015

Kilmartin-Lynch, S., Saberian, M., Li, J., Roychand, R., & Zhang, G. (2021). Preliminary evaluation of the feasibility of using Polypropylene Fibres FROM COVID-19 single-use face masks to improve the mechanical properties of concrete. *Journal of Cleaner Production*, *296*, 126460. https://doi.org/10.1016/j.jclepro.2021.126460

Kilmartin-Lynch, S., Roychand, R., Saberian, M., Li, J., & Zhang, G. (2022a). Application of COVID-19 single-use shredded nitrile gloves in structural concrete: Case study from Australia. *Science of The Total Environment*, *812*, 151423. https://doi.org/10.1016/j.scitotenv.2021.151423

Kilmartin-Lynch, S., Roychand, R., Saberian, M., Li, J., Zhang, G., & Setunge, S. (2022b). A sustainable approach on the utilisation of COVID-19 plastic based isolation gowns in structural concrete. *Case Studies in Construction Materials*, *17*. https://doi.org/10.1016/j.cscm.2022.e01408

Massarra, C., Rahat, M. H. H., Wang, G., & Sadek, H. (2022). Evaluating the cost of collection, processing, and application of face masks in hot-mix asphalt (HMA) pavements. *Heliyon*, *8*(11), e11239.

Morganti, P. (2020). Surgical & Beauty Facial Masks: The new waste problem of post covid-19. *Biomedical Journal of Scientific & Technical Research*, *29*(5). https://doi.org/10.26717/bjstr.2020.29.004878

Prata, J. C., Silva, A. L. P., Walker, T. R., Duarte, A. C., & Rocha-Santos, T. (2020). Covid-19 pandemic repercussions on the use and management of plastics. *Environmental Science & Technology*, 54(13), 7760–7765. https://doi.org/10.1021/acs.est.0c02178

Pandit, P., Maity, S., Singha, K., Annu, Uzun, M., Shekh, M., & Ahmed, S. (2021). Potential biodegradable face mask to counter environmental impact of covid-19. *Cleaner Engineering and Technology*, *4*, 100218. https://doi.org/10.1016/j.clet.2021.100218

Rahat, M. H., Massarra, D. C., & Wang, D. G. (2022a). Using plastic wastes in construction: Opportunities and challenges. *EPiC Series in Built Environment*. https://doi.org/10.29007/6369

Rahat, M. H. H., Karmakar, A., & Madani, M. A. U. Z. (2022b). THE EFFECT OF STEEL SLAG POWDER ON HMA STABILITY. *Malaysian Journal of Civil Engineering*, *34*(2), 37-43.

Rivas, K. (2020, November 25). Coronavirus face masks can be reused with 'dry heat,' FDA says. Fox News. https://www.foxnews.com/health/coronavirus-face-mask-reused-dry-heat-fda.

Royo-Bordonada, M.A., García-López, F.J., Cortés, F., & Zaragoza, G.A. (2020). Face masks in the general healthy population. *Scientific and ethical issues. Gaceta Sanitaria.* https://doi.org/10.1016/j.gaceta.2020.08.003

Saberian, M., Li, J., Kilmartin-Lynch, S., & Boroujeni, M. (2021). Repurposing of COVID-19 single-use face masks FOR pavements base/subbase. *Science of The Total Environment*, *769*, 145527. https://doi.org/10.1016/j.scitotenv.2021.145527

Tavares, G., Zsigraiova, Z., Semiao, V., & Carvalho, M. G. (2009). Optimisation of MSW collection routes for minimum fuel consumption using 3d GIS modelling. *Waste Management*, *29*(3), 1176–1185. https://doi.org/10.1016/j.wasman.2008.07.013

Tejaswini, M. S. S. R., Pathak, P., Ramkrishna, S., & Ganesh, P. S. (2022). A comprehensive review on integrative approach for sustainable management of plastic waste and its associated externalities. *Science of The Total Environment*, 825, 153973. https://doi.org/10.1016/j.scitotenv.2022.153973

Wang, G., Li, J., Saberian, M., Rahat, M. H., Massarra, C., Buckhalter, C., Farrington, J., Collins, T., & Johnson, J. (2022). Use of COVID-19 single-use face masks to improve the rutting resistance of Asphalt Pavement. *Science of The Total Environment*, 154118. https://doi.org/10.1016/j.scitotenv.2022.154118

Zhou, Y., Wang, Q., & Zhang, K. (2022). Facemasks and the COVID-19 pandemic: The harm caused by improper use of facemasks is a matter of concern. https://doi.org/10.22541/au.164864806.63311339/v1

Development of a BIM-based Immersive Environment: Challenges and Lessons Learned

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Creating a Virtual Reality (VR) walkthrough from a 3D building information model leads to fewer mistakes and enhanced project visualization. Visualizing a 3D model in VR reveal errors not easily seen with Building Information Modeling (BIM) software. This process helps on limiting future change orders and rework, saving time and costs for both the contractor and the owner. Immersive Virtual Reality (IVR) has capable of visualizing clash detection tools while walking around the model. IVR enables the user to walk around the model freely. This helps inspect any design errors and omissions and facilitates correcting them before drawings get issued for construction. The research objective is to assess the benefits of the Immersive Virtual Reality (IVR) walkthrough compared to a 3D model alone. This study was conducted using the Oculus Rift S headset with hand controllers, Revit, and Enscape rendering software. The paper discusses the process used for creating VR walkthroughs through this low-cost but high-performance combination. This paper also discusses where the IVR was used to identify geometry and design mistakes and helped prepare the accurate as-built model.

Key Words: Virtual Reality, Building Information Modeling, Construction Technology, Immersive Environment, 3D Model Design

Introduction and Background

Virtual Reality (VR) is one of the most exciting pieces of technology being incorporated into the construction industry today. In general, the purpose of VR applications in the built environment is to deliver lifelike simulations of existing, future, or hypothetical scenarios, spaces, and facilities, whether the final goal of the application is to support design review, facility management, or workforce training. Paes et al. (2021) define VR in the built environment context as the experience of presence (of “being there”) in a simulated architectural environment. Immersive VR (IVR) simulations allow users to walk through and interact with the virtual environment in a first-person-view mode facilitating their understanding of a project's geometry, which contributes to minimizing construction, operation, and maintenance costs associated with flaws arising from poor design solutions or undetected design mistakes.

IVR has increased users' sense of presence in the virtual environment, leading to higher focus and attention levels while navigating the model (Paes et al., 2021). VR can also be used in the design phase by design professionals, contractors, and clients of a project. VR walkthroughs benefit design professionals, contractors, and project owners. Design professionals use this technique to find mistakes and correct them before drawings get issued for construction. Also, design professionals could use VR to show their work to clients to understand better how their finished building will look. Contractors can use VR to see how a building will look before construction begins or while it is in progress. A better understanding of the finished product will help contractors make decisions early in the construction process. Finally, VR benefits project owners because they may only have limited experience with construction documents; therefore, VR could be the only way to understand what their building will look like when completed.

VR models have been built to evaluate a prospective building's structural integrity, design, and alternative solutions (Sampaio et al., 2010). VR helps to prevent expensive rework and/or potential structural failure resulting in severe injury or death. VR is used to monitor job progress from anywhere. Researchers have found that some businesses use VR to model tasks that are in progress on job sites for review by off-site personnel (Zaker and Coloma, 2018). The same study stated that the most significant obstacles to VR in construction are the industry's resistance to change and the cost of VR devices and compatible software (Zaker and Coloma, 2018).

Hilfert and Konig (2016) highlight the need for low-cost VR solutions in construction, which uncovered simple methods that would allow any company member to develop VR models without programming experience. Decreasing the cost of VR technology opens the door to more possibilities, including the use of VR in the field of interior design. Companies have begun to use VR to design interiors and make design changes using VR technology, giving consumers a better picture of how their space will look upon completion (Kaleja and Kozlovska, 2017). However, VR is not without obstacles. Since VR is a relatively new technology, companies find it costly to keep up with the most up-to-date hardware, software, and advancements (Alizadehsalehi et al., 2020). Another exciting feature of VR technology in construction is in the educational sector. Eiris et al. (2019) explain how site visits are vital to the construction curriculum. However, many students cannot visit construction sites for various reasons. With the help of VR technology, more students can virtually walk through sites and experience what they are being taught in the classroom. Elgewely (2021) adds that through this teaching style, students showed a thirty percent increase in learning improvement compared to paper-based methods, which showed a thirteen-point eight percent increase. There is more to VR usage in the classroom, however. The use of VR increases student involvement, and if the costs of VR technology come down, it could enhance e-learning during the COVID-19 pandemic (Alizadehsalehi et al., 2021).

This study was conducted using the Oculus Rift S headset with hand controllers and Enscape rendering software. This combination was reviewed by Huang (2018) and Paes et al. (2021) and determined to be effective, especially for educational purposes, due to its low cost but high performance.

Objectives

The main objective of this study was to investigate how to create an IVR walkthrough from a Revit model. Also, the research aimed to assess the benefits of the IVR walkthrough compared to a 3D model alone. The process discussed in this paper will take a Revit model and convert it to a desktop-based VR platform, and then a VR headset will be used to immerse the user into the same virtual environment.

Methodology

VR is used to enhance the visualization of construction projects before they are built or to view projects when a physical site visit is unsuitable. The process used in this research was to take the given PDF drawings of the existing Kennesaw State University's Campus and convert them into CAD drawings. These were then loaded into Revit, where a 3D model was developed. Developing this model included visiting the building to capture photos to ensure the model was as close to the actual building as possible. The rendering software Enscape was then procured and downloaded. Using an Oculus Rift S connected to the desktop computer running Revit via USB and Display port cables, the Oculus software, and SteamVR software, the researcher, was able to walk around the Revit model using the Oculus's hand controls and view the building in more detail than using Revit alone. This enhanced detail made design errors more apparent, and while changes cannot be made in the Enscape software, changes can be made on the host desktop computer and updated live in the virtual environment.

Development of the BIM Model

To develop an IVR walkthrough, one must first have a building 3D model. For the building selected in this study, no AutoCAD file existed for any of the three floors. Only PDF files were supplied. Figure 1 shows the floor plan CAD drawings. Therefore, the PDF files had to be imported into the AutoCAD software and redrawn in CAD format. Once the CAD drawings were completed, they were imported into Revit and redrawn again as a 3D model. Next, a site survey was conducted to gather photographs of Kennesaw State University. Following the site survey, edits were made to correct defects in the supplied PDF drawings. Once the Revit model was completed to match the actual building as close as possible, it was ready to convert into an IVR walkthrough in Enscape. In AutoCAD, the room tags were removed to make the model cleaner for import to Revit. The measurements of the ramps and level changes in the auditorium were kept for reference purposes in Revit. Figures 2, 3, and 4 depict all floor plans in Revit and the 3D model. Figure 2 is the third floor, Figure 3 is the second floor, and Figure 4 is the first floor. These floor plans were drawn in Revit using the CAD drawings as a reference. Based on the site survey, the materials picked for the model elements reflect the actual building as best as possible. The Enscape software allows users to import site context, meaning that the user can enter the geographical site address and place the model into that exact location. Enscape loads the surrounding buildings, roads, and topography for a more realistic view. Figure 5 is the 3D model of the building in the Enscape software.

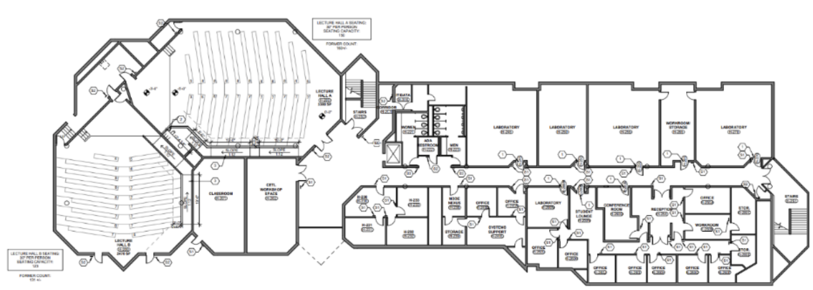

Figure 1: Floor plan (CAD drawings)

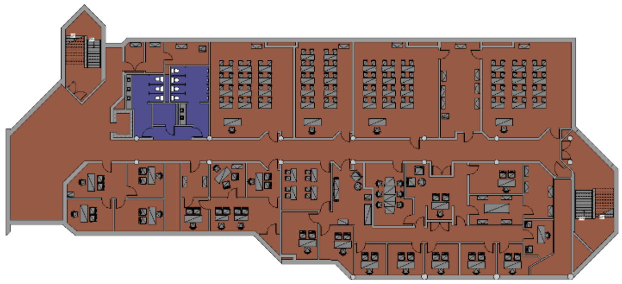

Figure 2: Third floor of the building

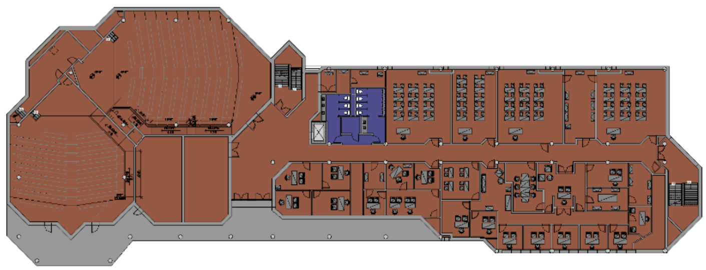

Figure 3: Second floor of the building

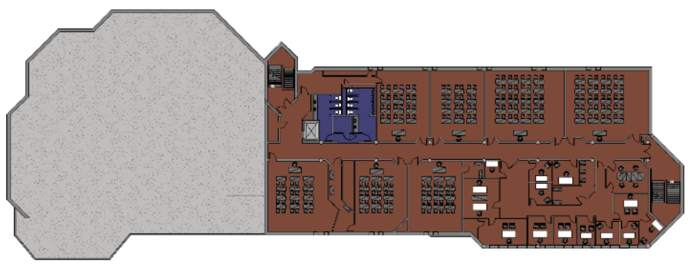

Figure 4: First floor of the building

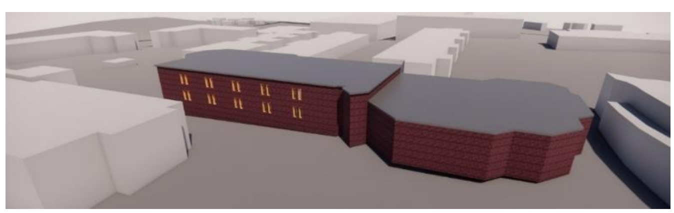

Figure 5: 3D model of the building in the Enscape software

BIM-based IVR Simulation

This study used an Oculus Rift S headset to set up the IVR system. The Oculus Rift S requires a connection to a computer via a USB Type-A connection and a Display port connection. A Display port to a USB Type-C adapter was needed to connect to the computer used in this study. After all, the hardware was acquired, the Enscape software was downloaded from the Enscape website. Enscape software integrates into Revit automatically and projects the VR walkthrough onto the computer desktop. To get the image to appear on the Oculus Rift S headset, SteamVR must be downloaded.

SteamVR creates a link between the computer and the headset. It works similarly to adding a second monitor, whereas whatever is projected on the computer screen is launched into the headset. Once the link is created, a user puts the headset on and walks through the Revit model using the hand controls that come with the Oculus Rift S. No model edits can be made in the Enscape software; however, users can navigate and take screenshots. Enscape also allows for live updates. This means that a second user can edit the Revit model using the host computer, which will update automatically in the Enscape virtual environment.

Using IVR, the walkthrough was observed across the building in real life and the VR simulation. Figure 6 shows a comparison of the front entrance of the building in real life and the VR simulation. The curtain wall mullions had to be edited in Revit, and the ceiling had to be made at an angle to match the actual building. Figure 7 is a comparison between the existing building's main lobby and the lobby in the VR walkthrough. The ceiling and floor materials could not be found; therefore, an exact match could not be made. However, the floor plan matches the drawings provided. IVR walkthrough also observed auditoriums from inside the Enscape software. These rooms' changing levels and ramps made this the most difficult room to model. Figure 8 depicts the second-floor hall near the bathroom. Again, the brick floor texture could not be found, so it was not used. Figures 9 shows the men's bathroom inside the actual building and the VR walkthrough. Enscape could not render the bathroom countertop or the sink element from Revit. Enscape also did not render the tile flooring as well as expected. All plumbing fixtures were rendered correctly, including the urinals and water closets. Figure 10 shows a comparison of a typical classroom. This classroom is on the third floor in the construction management department. The exact desks were unavailable; however, Enscape offers its material library, and the desks depicted came from that library.

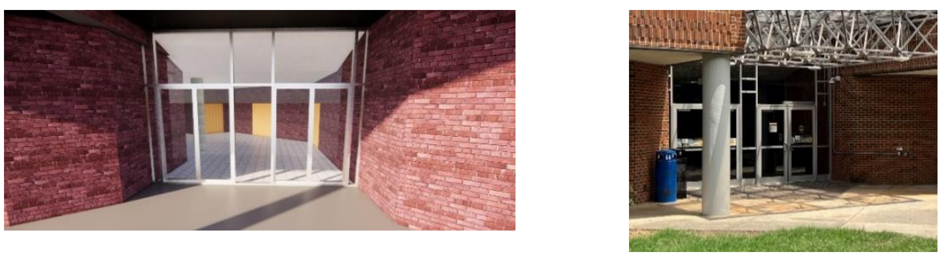

Figure 6: Front entrance, VR walkthrough vs. physical building

Figure 7: Main lobby, VR walkthrough vs. physical building

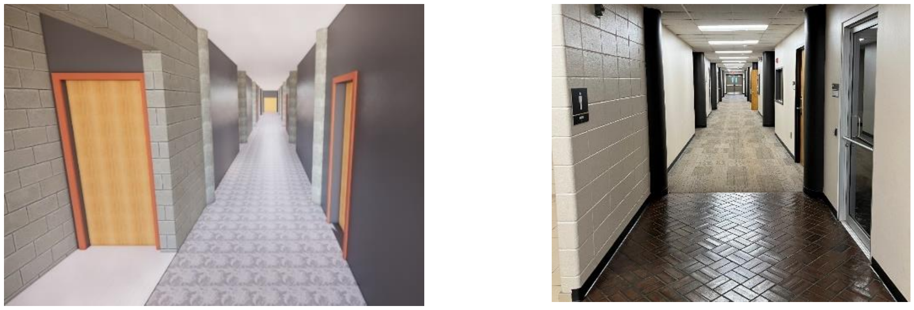

Figure 8: Hallway, VR walkthrough vs. physical building

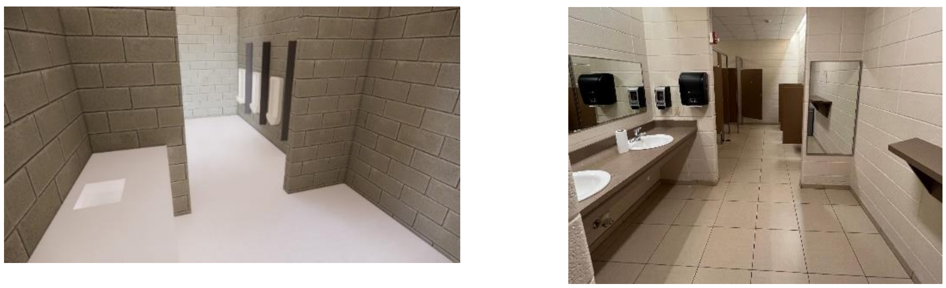

Figure 9: Men’s bathroom, VR walkthrough vs. physical building

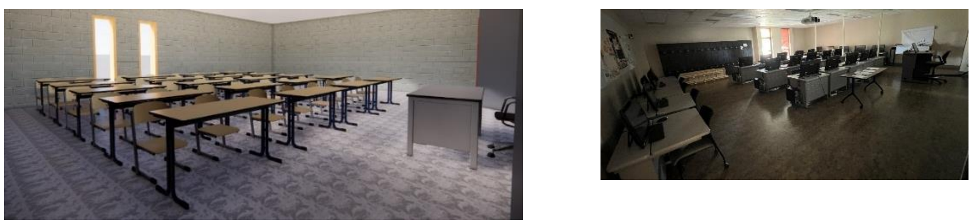

Figure 10: Classroom, VR walkthrough vs. physical building

Analysis and Discussions

Some geometry mistakes were found after the IVR walkthrough was created. The IVR simulation facilitated the identification of these mistakes, which were corrected before the model was finalized. This phenomenon is similar to visual clash detection performed by professionals involved in the design process during design coordination meetings. The first mistake was a gap between the stairwell’s ceiling and the floor above, as shown in Figure 11. This mistake would be difficult to see in Revit and would have been missed if the VR walkthrough was not created. This was corrected by creating a short wall that connected the ceiling to the floor above. Another mistake was that a wall in the basement was shown to be made of brick and block. This mistake is shown in Figure 12. It happened because there were two separate walls (brick and block ones) on that floor in the Revit model. This mistake was easily fixed by deleting one of the walls and editing the remaining one. Again, it is unlikely that this mistake would have been discovered using Revit alone.

The main interior stairwell is depicted in Figure 13. Enscape did not correctly render the stairs causing them to appear in bright white. Material textures can be edited in Revit, and new ones can be created if they do not exist in the texture library. Another design mistake only discovered during the VR walkthrough was that the floor slab overlapped with the stairs in the west stairwell going from floor one to floor two, as shown in Figure 14. This mistake was fixed by editing the floor slab boundary in Revit. This mistake is visible in Revit but easily overlooked, whereas it was very apparent in VR. Additionally, in walk mode in the VR simulation, the software would not let the user move past this point which is how it was originally discovered. The construction management office hall is shown in Figure 15. The actual doors could not be found, so the standard Revit doors were used. Also, the floor plan did not seem to match; therefore, the door spacing is not exact. Object library limitations (i.e., the low variety of objects such as doors) are still bottlenecks in converting from Revit to VR. The VR simulation ends up not being that similar to the actual building. However, like textures, doors can also be edited in Revit, and new ones can be created.

Figure 11: Geometry error: the gap between the ceiling and the floor

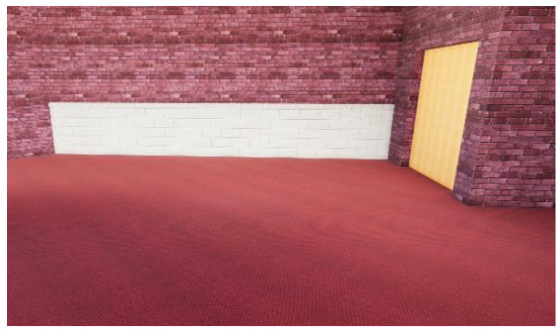

Figure 12: Geometry error: wall in the basement was shown to be made of brick and block

Figure 13: Design error: render the stairs causing them to appear in bright white

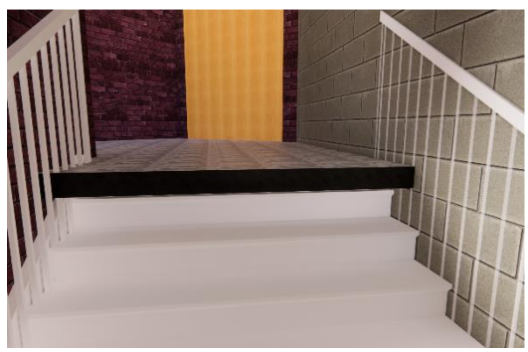

Figure 14: Design mistake: the floor slab overlapped with the stairs

 

Figure 15: Mismatch hallway doors at VR walkthrough and physical building

Conclusion

This study successfully created an IVR walkthrough of Kennesaw State University's Campus. The integration of site context was an unexpected benefit of the Enscape software; however, it was useful in seeing how the building fit on the school campus. Other benefits included finding clashes not seen in Revit alone, using Enscape's material library, and seeing the model from different viewpoints that are difficult to set in Revit. The process used in this study was found through trial and error; however, it was a straightforward process. Care should be taken to how the BIM model is developed for IVR simulation. The modeling process should mimic the as-built arrangement, so the reconstructed building is as close as possible to the physical one.

Design and contracting firms could easily use this technology in day-to-day operations. The costs saved from detecting a single future change order could return the investment of the hardware and software licenses required. Other applications of mixed-reality technologies, such as AR (Augmented Reality), involve using see-through head-mounted displays (HMDs) projecting a BIM model on top of live views of the site for construction progress inspection, ensuring that the building is completed as drawn. VR and AR combined could substantially reduce the frequency of change orders, mistakes, and rework in the construction sector. Future study is to check by enabling clash detective using VR by incorporating mixed-reality technologies to reduce change order.

References

Alizadehsalehi, S., Hadavi, A., & Huang, J. C. (2020). From BIM to extended reality in AEC industry. Automation in Construction, 116, 103254. doi:10.1016/j.autcon.2020.103254

Alizadehsalehi, S., Hadavi, A., & Huang, J. C. (2021). Assessment of AEC students' performance using BIM-into-VR. Applied Sciences, 11(7), 3225. doi:10.3390/app11073225

Eiris Pereira, R., & Gheisari, M. (2019). Site visit application in construction education: A descriptive study of faculty members. International Journal of Construction Education and Research, 15(2), 83-99. doi:10.1080/15578771.2017.1375050

Elgewely, M. H., Nadim, W., ElKassed, A., Yehiah, M., Talaat, M. A., & Abdennadher, S. (2021). Immersive construction detailing education: Building information modeling (BIM)–based virtual reality (VR). Open House International, 46(3), 359-375. doi:10.1108/OHI-02-2021-0032

Hilfert, T., & König, M. (2016). Low-cost virtual reality environment for engineering and construction. Visualization in Engineering, 4(1), 1. doi:10.1186/s40327-015-0031-5

Huang Ph. D, Y., & Odeleye, T. (2018). Comparing the capabilities of virtual reality applications for

architecture and construction. ASC Annual International Conference Proceedings, 54, 346-354.
Kaleja, P., & Kozlovská, M. (2017). Virtual reality as innovative approach to the interior designing. Selected Scientific Papers: Journal of Civil Engineering, 12(1), 109-116. doi:10.1515/sspjce-2017-0011
Paes, D., Irizarry, J., & Pujoni, D. (2021). An evidence of cognitive benefits from immersive design review: Comparing three-dimensional perception and presence between immersive and non-immersive virtual environments. Automation in Construction, 130. doi: 10.1016/j.autcon.2021.103849
Sampaio, A. Z., Ferreira, M. M., Rosário, D. P., & Martins, O. P. (2010). 3D and VR models in civil engineering education: Construction, rehabilitation, and maintenance. Automation in Construction, 19(7), 819-828. doi:10.1016/j.autcon.2010.05.006
Wang, P., Wu, P., Wang, J., Chi, H., & Wang, X. (2018). A critical review of the use of virtual reality in construction engineering education and training. International Journal of Environmental Research and Public Health, 15(6), 1204. doi:10.3390/ijerph15061204
Zaker, R., & Coloma, E. (2018). Virtual reality-integrated workflow in BIM-enabled projects collaboration and design review: A case study. Visualization in Engineering, 6(1), 1-15. doi:10.1186/s40327-018-0065-6

Understanding Career Opportunities for Construction Graduates within the Roofing Industry Distribution Sector

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The construction industry continues to grow rapidly and faces a massive shortage of workers. The roofing industry, in particular, is projected to grow considerably with an increased demand for workers in the upcoming years. One critical component of the roofing industry is distribution. Distributors play a significant role in ensuring that materials arrive on site in a timely and affordable manner and act as a bridge between the roofing subcontractors and manufacturers. Attracting the next generation, Generation Z (Gen Z), is critical to address workforce shortages in the industry. The Gen Z population has various career preferences and characteristics that influence them in selecting a career. Gen Z looks for a defined career path within a specific industry that shows how their career can grow over time. This paper aims to develop and document a typical career path that college students from a construction program might have within the distribution sector of the roofing industry,with the help of a focus group. Additionally, the focus group discussed information regarding worker responsibilities, experience requirements, compensation, and benefits for each position. This paper documents the consensus findings from the focus group. This information and flowchart will aid educators and industry members in garnering interest in the distribution sector of the roofing industry.

Key words: Generation Z, Career Path, Workforce, Roofing Distributors

Introduction

The U.S. Construction industry employs about 6% -10% of the total workforce and significantly contributes to the U.S. economy (Assaad & El-adaway, 2021). The construction industry heavily influences the functioning of many other sectors, such as manufacturing, transportation, infrastructure, commercial spaces, etc. (Assaad & El-adaway, 2021; Azeez et al., 2019; Baral et al., 2022). A construction project requires a team effort with various parties involved in different areas of project execution, such as the general contractor, specialty contractors or subcontractors, material suppliers (also known as distributors), and manufacturers.

Subcontractors work on specialty areas and perform a specific scope of work, such as roofing, mechanical, electrical, plumbing, finishes, etc. However, for the sub-contractors to get material deliveries, they typically work closely with material distributors for timely delivery of materials and to get competitive pricing. Distribution services are defined as wholesale trade services, retailing services, franchising and commission agents' services, that act as a link between producers and consumers – ensuring that consumers have access to a large selection of products at affordable prices (World Trade Organization). Subcontractors greatly benefit from partnering with distributors as they ensure better quality, higher reliability, more variety and personalization, faster responses to variations in demand and decreased time to market (Biruk et al., 2019). Distributors in the construction industry play an important role in keeping up with project quality, schedule, and budget (Cengiz et al., 2017).

According to the U.S. Bureau of Labor Statistics, occupations related to construction make up more than one-fourth of the fastest-growing careers and the industry projects a growth rate of 4% from 2021 to 2031 (U.S. Bureau of Labor Statistics). Between 2018 and 2028, employment in the industry is expected to increase by 10%, with over 800,000 new job openings (Callanan & Perri, 2020). In the second quarter of 2022, the construction industry contributed to 3.9% of the US GDP according to the US Bureau of Economic Analysis. Research shows that the current labor shortage will also likely increase in the construction industry (Carter 2022; Choi et al., 2022).The labor shortage and the expected increase in work demand will be problematic and must be addressed (Pandita, 2021). The average age of construction workers in the U.S. is 42.6 years, and by 2024, the percentage of workers in the age category of 55 and above is expected to double (Sokas et al., 2019). One concern brought up by the Department of Labor was the replacement of this aging workforce. Keeping up with this pace, it was expected that roughly 240,000 workers will need to be filled in (Kim, Chang, & Castro-Lacouture, 2020).

One of the important sectors in construction is the roofing industry. Similar to other sectors in the construction industry, the roofing industry is also expected to see considerable growth, thereby needing to bring in more workers (IBISWorld). According to the U.S. Bureau of Labor Statistics, the roofing industry employs 129,890 workers at a mean hourly wage of $23.51 (U.S. Bureau of Labor Statistics).The three main entities in the roofing industry include roofing subcontractors, distributors, and manufacturers. The distributor is an essential channel between the roofing subcontractor and manufacturer responsible for material handling and logistics, inventory management, quality, and training on the job site for roofing workers, providing credit to the roofing contractors and the delivery of roofing materials to the job site. Distributors also provide services such as estimating, technical services, QA/QC inspections, etc. As of 2022, three major roof distribution companies in the U.S. account for about 70% of the roofing distribution market and the roofing distribution sector employs 55,909 workers (IBISWorld, 2022). To keep up with the industry's growth and increasing demand, attracting and retaining professionals in the roofing distribution business is critical.

One of the ways to address the workforce shortage is to attract the Gen Z population and retain current professionals in the roofing industry. Gen Z tends to be ambitious, practical, and keen on challenges (Aggarwal, Sadhna, Gupta, Mittal, & Rastogi, 2020a). They are self-learners, possess strong multi-tasking abilities, and are the first digitally connected generation with constant technological access since birth (Becker, 2022). When considering a career, this generation tends to opt for an exciting workplace that avoids redundancy and provides job stability. They prefer a flexible working environment that will allow them to work independently and be mentored (Pandita, 2021). They do not believe in being confined to an office place and can get work done from anywhere using technological tools (Csiszárik-Kocsír & Garia-Fodor, 2018). However, one of the important aspects of this generation is a defined career path within a specific company and/or industry (Goh & Okumus 2020). Research shows that this generation is not afraid of switching jobs and choosing companies that give them a clear path to promotion with a work profile/description for each position (Aggarwal et al., 2020b). Unfortunately, one of the primary reasons the construction industry has failed to attract the younger generation so far is the lack of sufficient information regarding career paths and training (Hiranya Delvinne, Hurtado, Smithwick, Lines, & Sullivan, 2020).

The literature review shows that the roofing distribution business is a critical sector in the construction industry. Like other sectors, the distribution sector will need a workforce to meet the growing demands of the industry (IBISWorld). The skills required to work in the distribution sector of the industry align with those of students who graduate from construction management programs, thus allowing a viable path to a career for these students in this industry sector. Currently, a clear visual career path and the details of each position in the roofing distribution sector are lacking to attract Gen Z and retain current professionals, especially for those coming from a construction management degree program. To that effort, the objectives of this paper are to 1) Document the different types of positions and their description within the roofing distributor organization suitable for someone with an undergraduate construction management degree, 2) Analyze the compensation for each type of position, 3) Document the benefits for each position, 4) the type of experience required for each position and promotion/vertical movement expectations and 5) Generate a visual career path focused on roofing distributor organizations.

Methods

Figure 1 shows this study's four (4) phase research methodology. The methodology is adopted from the study conducted to document the visual career path for the roofing contractors (lucas et al., 2022)

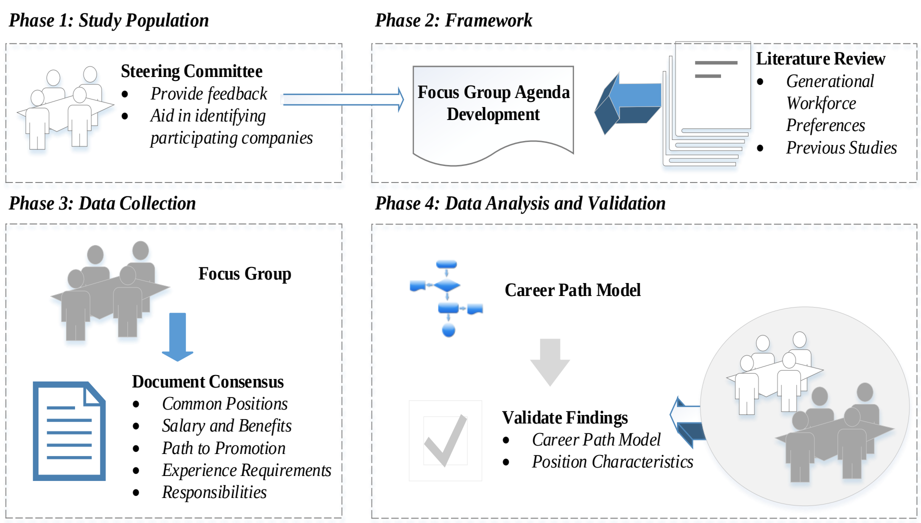

Figure 1. Phases of Methodology

Phase 1: A steering committee was formed to assist in developing the study framework, provide validation, and select the participating companies from the roofing industry. Out of the three (3) major roofing distributors in the U.S., two (2) roofing distributors participated in the focus group over Zoom. The two participants hold CEO positions with the roofing distribution companies and are in charge of the national level management of the companies. The two roofing distributor companies represented about $10B of the roofing material supply market with over 10,000 employees. Due to the focused nature of the roofing distribution sector, the steering committee agreed that this was a good representation of the sample.

Phase 2: An in-depth literature review on generational workforce preferences was used to create the focus group agenda. Items for discussion included employee positions, salary and benefits, a path to promotion, experience requirements, and responsibilities. The steering committee validated the focus group agenda by ensuring that it met the study's objectives.

Phase 3: Data were collected through discussions among two (2) roofing distributor companies. The primary participants of the distributor companies were the president and owner that had in-depth knowledge about their company structure and characteristics. There were three focused discussion points:

a. Different types of positions within the company.
b. Job responsibilities, salary, benefits, and experience required for each position.
c. Identifying the typical career path that maps entry-level through upper-level positions in the roofing industry.

The data were collected and documented in real-time by giving dedicated discussion time to each distributor and then reaching a consensus after each discussion point.

Phase 4: The data collected were analyzed to develop a general career path for roofing distributor companies. Each position was analyzed and compared regarding responsibilities, experience requirements, compensation, and benefits. The mapped career path and documented information were validated with the steering committee and the two (2) distributor companies participating in the focus group.

Analysis Results

Positions and Responsibilities

The positions in the roofing distribution sector where construction management graduates could be employed fall into two categories: sales/service (technical sales and technical services) and management (branch manager, district manager, regional vice-president and executive position). The data indicates that, as seen in most organizations and occupations, entry-level positions come with the least number of responsibilities. As a person climbs the hierarchical ladder of the organization, they are laden with more duties and responsibilities. The management trainee in a roofing distributor organization has a narrow range of duties compared to the branch manager, who has a broad range of responsibilities. The entry-level positions focus more on general training to get acquainted with the nature of business and manage day-to-day sales. In contrast, higher positions are seen to be requiring more leadership and management skills. The management trainee gets a good overview of various aspects of the distribution business aided by the rotational nature of the position. The demand for leadership skills also increases depending on the level of management within the company's hierarchy. The branch manager focuses on the operations of the specific unit, while the regional vice-president oversees multiple units within the region and leads district managers. The findings for the individual positions are outlined below in *Table 1*.

Table 1

Responsibilities for various positions

Position	Responsibilities
Management Trainee	Rotational training to be a Branch Manager to gain knowledge of the overall distribution operations.

Technical Sales	Inside and outside sales to acquire new business and the role of customer consultant.
Technical Services	Quantity take-offs and estimating
Branch Manager	Managing the business unit or the specific branch and all of its operations.
District Manager	Managing multiple branches, providing leadership and mentorship to branch managers.
Regional Vice-president	Managing multiple branches that are allotted within the specified region, providing leadership and mentorship to district managers.
Executive	Managing and leading operations, procurement and logistics.

Compensation

Higher compensation usually accompanies higher positions that require greater expertise and knowledge. The data collected shows a steady increase in compensation as the employee progresses in their career. From the entry-level management trainee position to the position of technical services, there is a 39% increase in compensation. However, it must be noted that technical services salary heavily depends on the number of years in the position. Focus group participants noted that some employees prefer to remain in the technical services position for their entire career, which can result in an increase in salary. On the management side, there is a considerable increase in salary from branch manager to executive, which corresponds to their experience and scope of responsibilities. The highest-paid position in a roofing distributor organization is the executive position. Compared to the management position, the sales positions have lower compensation; however, the sales team also has an opportunity to make a commission of up to $100,000 annually on sales. Generally, the salaries for each position in the distribution sector match or exceed the industry average.

A detailed matrix of compensations and benefits for each position is outlined in Table 2.

Table 2

Position Compensations

Position	Average	Range
Management Trainee	$45,000	$40,000 - $50,000
Technical Sales	$47,500	$45,000 - $55,000
Technical Services	$62,500	$50,000 - $75,000
Branch Manager	$100,000	$100,000 and above
District Manager	$120,000	$90,000 - $150,000 and above
Regional Vice-President	$375,000	$250,000 - $500,000 and above
Executive	$375,000	$250,000 - $500,000 and above

Benefits

There is no variation in benefits across the career path for both the sales/services and management sectors. All positions receive the same benefits that include insurance (health, vision, dental), 401K match, bonuses (depending on the company), equity sharing (depending on the organization structure), profit sharing bonus, and paid time off. However, the technical sales position receives an additional benefit. Along with standard benefits such as insurance (health, vision, dental), 401K match, profit sharing bonus, paid time off, and base salary, they also receive a commission. Consistent benefits are critical since it ensures the same care and coverage from the company, irrespective of any position. The benefits offered by distribution companies align with industry standards.

Experience

The experience required for entry-level positions is minimal, with more emphasis placed on training programs or college degrees. For higher positions, priority is given to those with experience. For an employee to be promoted to a higher position, they must have worked in the organization for a minimum number of years and should have proven their capabilities. The typical experience required for promotion from entry-level positions such as management trainee or technical sales to branch manager could be between four to seven years. This could be accelerated based on factors such as employee performance or company requirements. The climb from management trainee to technical services positions is not steep. It should be noted that positions often overlap in a career path. For example, a person in the position of technical services could be qualified to take up a branch manager position based on experience. The experience requirements for the individual positions are outlined below in *Table 3*.

Table 3
Experience requirements

Position	Experience required
Management Trainee	Prior technical sales and service experience and / or a bachelor's degree or master's degree
Technical Sales	Entry level position for roofing distributors
Technical Services	Technical sales experience and / or a two-year associate degree
Branch Manager	Completed management in training program, outside sales experience, additional financial understanding beyond a construction degree
District Manager	Extensive experience as a Branch Manager
Regional Vice-president	Extensive experience as a District Manager
Executive	Extensive experience as a District Manager and/ or Regional V.P.

Career Path

The typical career path within a roofing distributor company is shown in *Figure 2*. A potential worker entering the roofing distributor organization can choose either the sales/services or the management path.

A recent college graduate looking for an entry-level position within roofing contracting companies would be employed as a management trainee or in the technical sales/ services position based on their background and qualification. Over time this employee will progress in rank throughout their career. Regional vice president and executive-level positions generally require extensive experience within the roofing industry.

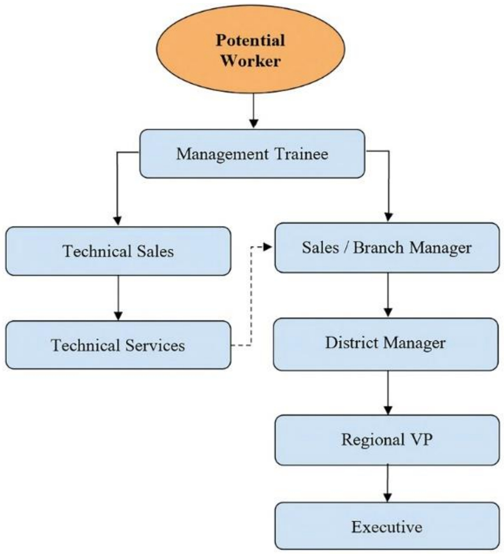

Figure 2. Visual Career Path Model

Conclusion

The main objective of this study was to clearly define and document a visual career path for the roofing distributor sector of the industry so construction management graduates could consider this sector for employment upon graduation. The entry-level positions in the sector have a narrow scope of responsibilities and are more focused on training, whereas the higher positions have a broader scope of duties. With higher positions comes the demand for leadership. While a branch manager has to be equipped to handle the workings of a particular branch, a district manager must be equipped to handle the workings of multiple branches and lead many branch managers. As seen in most organizations, compensation is higher for top managerial positions when compared to entry-level and sales/services positions. This is because of the experience and knowledge that these positions require and the higher level of responsibility attached to the position. Sales positions have comparatively lower compensation, but they get commissions on sales to compensate for some part of it. Entry-level positions require little to no prior experience and focus on training programs that can benefit from college degrees. On the other hand, higher positions rely heavily on previous experience. Employees might need to invest four to seven years in the company to get promoted to a higher managerial position. The benefits offered to all positions are the same except the technical sales position, which gets a base salary plus commission.

Roofing distribution organizations are often large firms with a large number of employees. These firms provide employees with desirable working conditions and consistent care through company benefits. Distributors play an important role in the supply chain between roofing contractors and manufacturers. Working in the distributor sector is challenging and is far from being tied to an office space or desk, which makes it a desirable option for the Gen Z population. There is freedom, job stability, mentorship and the possibility to grow in the sector. The literature review showed the importance of having a visual career path and different career positions to attract a younger workforce. This visual career path and the job responsibilities, compensation, benefits, and salary will provide Gen Z a viable career option to consider. Roofing distributors can also use the study's results to train and create awareness amongst new and existing employees. The flowchart gives a clear understanding of the expected career trajectory within the sector.

The limitation of this study is that the focus group participants are representatives of the roofing distribution sector only in the U.S. There is still the need to analyze job responsibilities and map career paths for other distribution sectors of the construction industry. This research paves a starting point to attract and retain Gen Z sector into the roofing distribution sector. There needs to be further research to understand other factors that possibly affect and influence Gen Z career preferences.

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References

Aggarwal, A., Sadhna, P., Gupta, S., Mittal, A., & Rastogi, S. (2020a). Gen Z entering the workforce: Restructuring HR policies and practices for fostering the task performance and organizational commitment. *Journal of Public Affairs*. https://doi.org/10.1002/pa.2535

Assaad, R., & El-adaway, I. H. (2021). Impact of Dynamic Workforce and Workplace Variables on the Productivity of the Construction Industry: New Gross Construction Productivity Indicator. *Journal of Management in Engineering*, *37*(1). https://doi.org/10.1061/(asce)me.1943-5479.0000862

Azeez, M., Gambatese, J., & Hernandez, S. (2019). What Do Construction Workers Really Want? A Study about Representation, Importance, and Perception of US Construction Occupational Rewards. *Journal of Construction Engineering and Management*, *145*(7). https://doi.org/10.1061/(asce)co.1943-7862.0001669

“BEA Industry facts”. (2022). *U.S Bureau of Economic Analysis.*

Baral, A., Liang, Y., Li, M., Gonzalez, M., Shahandashti, M., & Asuri, B. (2022). Impact of Covid-19 on the Diversity of the Construction Industry. *American Society of Civil Engineers.*

Becker, K. L. (2022). We want connection and we do not mean wi-fi: examining the impacts of Covid-19 on Gen Z’s work and employment outcomes. *Management Research Review*, *45*(5), 684 699. https://doi.org/10.1108/MRR-01-2021-0052

Biruk, S., Jaskowski, P., & Czarnigowska, A. (2019). Fuzzy AHP for selecting suppliers of construction materials. *IOP Conference Series: Materials Science and Engineering*, *603*(3). Institute of Physics Publishing. https://doi.org/10.1088/1757-899X/603/3/032093

Callanan, G., & Perri, D. (2020). Constructing construction careers: the case for the building trades. *Education and Training*, *62*(3), 201–213. https://doi.org/10.1108/ET-06-2019-0117

Carter, A. (2022). *Perceptions of Construction Trade Careers Amid a Growing Labor Shortage: An Exploratory Study*.

Cengiz, A. E., Aytekin, O., Ozdemir, I., Kusan, H., & Cabuk, A. (2017). A Multi-criteria Decision Model for Construction Material Supplier Selection. *Procedia Engineering*, *196*, 294–301. Elsevier Ltd. https://doi.org/10.1016/j.proeng.2017.07.202

Choi, J. O., Shane, J. S., & Chih, Y.-Y. (2022). Diversity and Inclusion in the Engineering Construction Industry. *Journal of Management in Engineering*, *38*(2). https://doi.org/10.1061/(asce)me.1943-5479.0001005

Csiszárik-Kocsír, Á., & Garia-Fodor, M. (2018). Motivation analysing and preference system of choosing a workplace as segmentation criteria based on a country wide research result focus on of Z. *Online Journal Modelling the New Europe*, (27), 67–85. https://doi.org/10.24193/OJMNE.2018.27.03

Goh, E., & Okumus, F. (2020). Avoiding the hospitality workforce bubble: Strategies to attract and retain generation Z talent in the hospitality workforce. *Tourism Management Perspectives, 33*. https://doi.org/10.1016/j.tmp.2019.100603

Hiranya Delvinne, H., Hurtado, K., Smithwick, J., Lines, B., & Sullivan, K. (2020). *Construction Research Congress*.

"Industry Market Research, Reports, and Statistics" (2022). *IBISWorld*

Kim, S., Chang, S., & Castro-Lacouture, D. (2020). Dynamic Modeling for Analyzing Impacts of Skilled Labor Shortage on Construction Project Management. *Journal of Management in Engineering*, *36*(1). https://doi.org/10.1061/(asce)me.1943-5479.0000720

lucas, jason, & gajjar, dhaval. (n.d.). *Roofing Industry Career Path*.

Matthews, J. ;, Pellew, L. ;, Phua, F. ;, Rowlinson, S., Matthews, J., Pellew, L., & Phua, F. (2000). Quality relationships: partnering in the construction supply chain FULL TEXT. In *The International Journal of Quality & Reliability Management ; Bradford* (Vol. 17).

Pandita, D. (2021). Innovation in talent management practices: creating an innovative employer branding strategy to attract generation Z. *International Journal of Innovation Science*. https://doi.org/10.1108/IJIS-10-2020-0217

"Roofers: Occupational Outlook Handbook" (2022). *U.S. Bureau of Labor Statistics*

Sokas, R. K., Dong, X. S., & Cain, C. T. (2019). Building a sustainable construction workforce. ***International Journal of Environmental Research and Public Health*, *16*(21).**

Attentional Impact of Drones on Construction Sites

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Drones are being widely deployed in construction, and the interaction between them and construction professionals is expected to increase even more in the future. However, the deployment of these aerial robots near construction professionals could be associated with additional risks affecting the safety and health of the workplace. This study explores the attentional impact of drone presence at different distances from construction professionals on the jobsite. Through a user-centered virtual reality-based experiment, construction professionals were asked to accomplish a construction task with the presence of drones while having their eye movement tracked. Results showed that the drone presence has an impact on participants' attentional states and that these aerial robots have attracted some of the construction professionals' attention. Participants' attentional state was also impacted by the drone operational distance, with professionals in close proximity from the drone looking fewer at the aerial robot, and for shorter durations, as opposed to those located at a farther distance. The contributions of this study are to ensure safe human-drone interaction in construction by informing industry personnel of the potential safety impacts of drones on jobsites and assisting in the formalization of specific regulations for the use of aerial robots in the industry.

Key Words: Drone, Attentional Allocation Impact, Construction Safety, Human-Drone Interaction, Proxemics

Introduction

The construction industry has recently started to integrate automation and robotics into day-to-day tasks to address skilled labor shortage, decreased productivity rates, and project inefficiencies (Davila Delgado et al. 2019). This integration stems from recent advancements, which enabled efficient technology development and sensor miniaturization (Javaid et al. 2021). Given that the construction industry always depends on human ingenuity and decision-making to accomplish different tasks, robots are currently being regarded as assistive and collaborative tools, rather than entities envisioned to replace human workers on jobsites. Compared to traditional methods, research has shown that robots in construction are able to efficiently collaborate with human workers to accomplish different construction tasks. In particular, drones have been recently used for a wide range of applications on jobsites, with construction being one of the top commercial adopters of this technology (Albeaino et al. 2019). Drones' wide deployment in construction stems from their flexibility and location-independency, the cost and time savings, as well as the safety improvements associated with their onsite usage, enabling them to be applied across all project phases, from pre-construction and construction to post-construction (Zhou et al. 2018). Application examples include site mapping and layout planning (Jiang et al. 2020), earthwork volumetrics (Siebert and Teizer 2014), progress monitoring (Ibrahim and Golparvar-Fard 2019), structure inspection (González-deSantos et al. 2020), safety management (Martinez et al. 2021), and building maintenance (Mutis and Romero 2019). This trend in drone technology adoption is projected to continue, and aerial robots are expected to become active collaborators, assisting human workers in various construction tasks such as bricklaying and material handling (Goessens et al. 2018; Zhang et al. 2022).

The unprecedented usage of drones in construction necessitates exploring the safety impacts of these aerial robots on humans working on construction jobsites. Construction in general, is a dynamic and hazardous work environment, and interacting with drones in such situations might expose workers to additional unsafe situations that have not been explored yet. For example, drone usage on jobsites has been associated with physical or contact risks, physiological risks, and attentional costs (Jeelani and Gheisari 2021). Namian et al. (2021) asked construction professionals about the safety challenges of drones on construction sites, and showed that these aerial robots are associated with various risks, including distractions. A negative construction professional attentional state could have adverse consequences on the workplace's health and safety. Distraction in particular, has been shown to affect construction professionals' ability to recognize hazards and perceive risks on jobsites (Cohen et al. 2017; Namian et al. 2018). Such factors not only cause some onsite hazards to remain unidentified, but also jeopardize construction professionals' safety performance and potentially result in unsafe practices that could lead to jobsite injuries and even fatalities (Ke et al. 2021). The introduction of drones to the jobsite could cause some professionals to divert their attention from the task at hand and onto the aerial robot. Therefore, understanding the potential impact of drones on construction professionals' attentional state is of particular importance, especially since these aerial robots are becoming more prevalent on jobsites.

There have been many studies on the drone application trends, benefits, and barriers within the construction industry (Albeaino and Gheisari 2021), and some researchers have even identified and theoretically discussed the potential safety challenges associated with the usage of this technology on jobsites (Namian et al. 2021; Xu and Turkan 2022). However, conducting experiments to empirically evaluate the safety implications of drones on construction jobsites is yet to be performed. The aim of this study is to investigate the attentional impacts of drones on construction jobsites. Whiles drones have been shown to potentially cause other risks such as physical and physiological risks (Jeelani and Gheisari 2021), the scope of this study is limited to evaluating the attentional costs associated with the presence of drones at different distances from construction professionals on the jobsite. More specifically, this study seeks to answer the following research questions: (1) Does the drone presence impact construction professionals' attentional state on jobsites? and (2) Does the drone operation distance impact construction professionals' attentional state on jobsites? To answer these research questions, a between-subject experiment was conducted, where recruited professionals had to accomplish a construction task in Virtual Reality (VR) with the presence of drones at either the (1) proximal distance or the (2) distal distance. These two distances were selected based on: (1) Hall's defined interaction distances (e.g., 1.5, 4, 12, and 25 ft) (Hall 1969); and (2) current and future drone applications in construction, with some requiring human-drone interactions at close distances and others at farther distances. Measures such as the Fixation Count (i.e., number of times users had looked at the drone) and Fixation Duration (i.e., average total duration each user spent fixating on the drone) were collected, analyzed, and compared between two drone distance groups. By exploring how construction professionals' attentional behavior is affected by the presence of drones at different operational distances (i.e., proximal and distal), this study provides industry personnel and agencies with a better understanding of the potential safety impacts associated with these aerial robots on jobsites. This ultimately helps overcome current non-specific drone regulations (Xu and Turkan 2022) by assisting in the formalization of specific and comprehensive regulations for the use of drones in construction.

Study Procedure

The aim of this study is to evaluate the potential impact of drones on construction professionals' attentional states. To accomplish this aim, the following two-step procedure was adopted (Figure 1): Step (1) –VR development; and Step (2): Assessment. In Step (1), the safety literature and the Occupational Safety and Health Administration (OSHA) incident investigation summaries were queried to identify most common high-risk activities and locations that could potentially become even more hazardous with the drone presence. The identified and selected high-risk scenario was then relied upon to develop a VR environment of a real-world construction jobsite while simulating the high-risk scenario with the presence of drones. Construction professionals were then recruited in Step (2) to empirically evaluate the impact of drones on their attentional states while accomplishing a task in the developed VR scenario.

Scenario Selection and VR Development

Jobsite injuries and fatalities occur mostly due to falls from roofs, ladders, and scaffolds, as evidenced by the safety literature and the OSHA incident investigation summaries in the US (Mendes et al. 2022; Nadhim et al. 2016). For this reason, a scaffolding scenario was identified and selected to be simulated in VR, especially since: (1) scaffolding operations cover most construction operations (e.g., inspecting, painting, roofing, carpentry); and (2) the introduction of drones to such operations – which have already been considered hazardous (Kang et al. 2017) – might expose professionals to additional hazardous situations. A slab was being prepared for formwork installation and concrete placement in the scaffolding scenario. Formwork installation and concrete placement activities were specifically selected since these operations have been typically associated with injuries and fatalities caused by, for example, trips, slips, nailing and hammering, material handling, and struck-by incidents (Hallowell and Gambatese 2009; Lipscomb et al. 2006; Rozenfeld et al. 2010).

The technical development of the VR scaffolding scenario consisted of converting 3D models of various construction jobsite components (e.g., buildings, machinery, scaffolds, formwork, reinforcing steel members) into .FBX files and importing them into an environment in Unity® (Figure 1). The scaffolding, slab, and formwork components were arranged to simulate formwork installation and concrete placement activities while being on scaffolds. Additional 3D models of different construction workers accomplishing various formwork installation and concrete placement activities (i.e., nailing, hammering, rebar tying, slab cleaning, scaffold members transporting) as well as cranes, vehicles, and other machines and equipment were also programmed, animated, and incorporated into the environment. To enhance the realism even more, special visual effects such as one simulating real-world dust and vehicle tire tracks were also applied. Proper sounds were also assigned to different equipment and machinery while enabling spatial audio effects. Drone sounds used were ones from a DJI® Phantom 4 Pro, one of the most popular platforms used in the construction industry (Albeaino and Gheisari 2021). A total of two VR scenes were created, with the only difference being the drone operational distance from the user. The selected drone operational distances were as follows: (1) Proximal: drone operating at 1.5 ft, simulating drone applications requiring close interaction with construction professionals; and (2) Distal: drone operating at 25 ft, simulating drone applications requiring farther interaction distances. The drone operational distances were selected based on: (1) Hall's defined Human-Human interaction distances (i.e., 1.5, 4, 12, and 25 ft) which are widely used in the Human-Drone interaction literature (Albeaino et al. 2022; Tezza and Andujar 2019); and (2) the current and future drone applications in construction, with some of them (e.g., material delivery, aerial construction) requiring human-drone interaction at close distances (e.g., 1.5 ft – proximal), and others (e.g., earthwork operations, site planning) necessitating interactions at farther distances (e.g., 25 ft – Distal). Except for the proximal and distal distances (i.e., 1.5 ft and 25 ft), the drone maintained a fixed height throughout the scene duration and remained within the users' field of views.

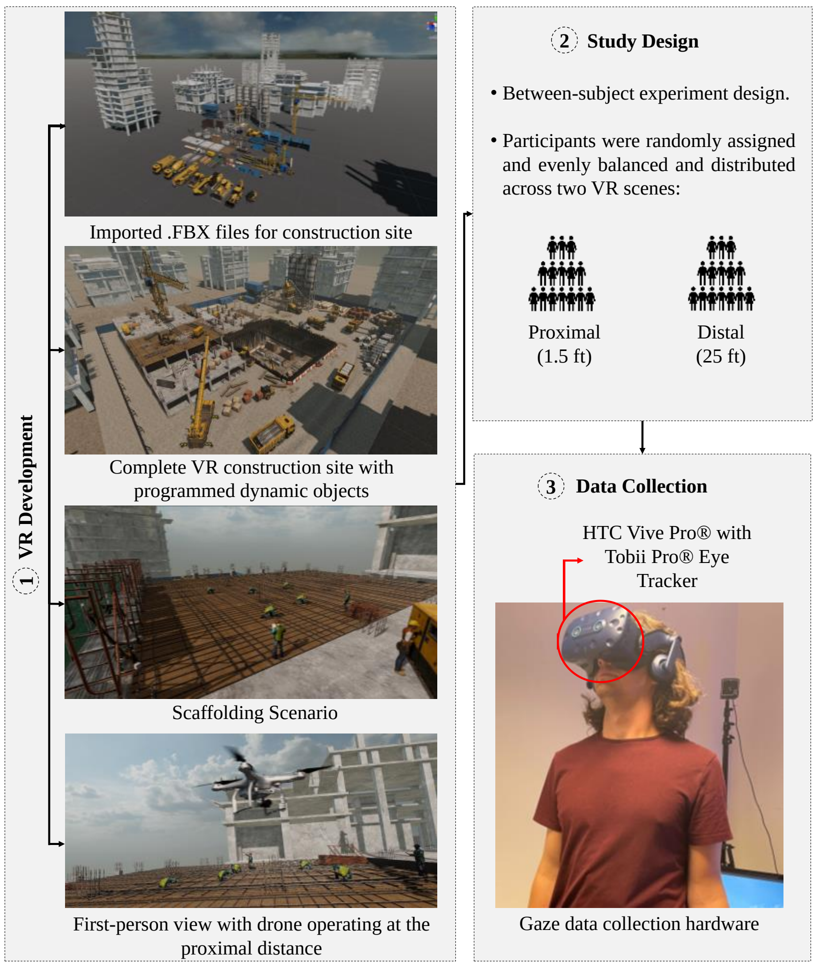

Figure 1. Adopted Procedure

Assessment Procedure and Attentional Metrics

Upon their agreement to participate in the experiment and signing the consent form, recruited participants were asked to fill out a demographics questionnaire and were then randomly assigned to one of the two drone distance VR scenes (i.e., Proximal and Distal). Participants were also asked to place and calibrate the HTC® head-mounted display (HMD) along with its built-in Tobi Pro® eye tracker to ensure proper gaze data collection before starting the experiment. Once in the VR scaffolding environment, participants were asked to act as jobsite supervisors and monitor construction workers' productivity by counting the number of scaffold members that a construction worker carries from one place to another. To ensure that they remain engaged during the experiment, subjects were also required to answer a few questions about the environment. Participants spent a total of three minutes in VR. During the first minute, no data collection was performed, as users were provided with an opportunity to explore and get familiar with the VR construction environment and the HMD. During the second two minutes, gaze data collection was performed while participants were in the process of accomplishing the construction task in VR with the presence of the virtual drone. The study was approved by the University of Florida Institutional Review Board (IRB #202102439) prior to participant recruitment and data collection.

The metrics used to evaluate participants' attentional states while accomplishing their tasks in VR were: (1) Fixation Count, which was determined by calculating the number of times users had looked at the aerial robot (Holmqvist et al. 2011); and (2) Fixation Duration, which was determined by summing up the total duration each user had spent fixating on the distractor (i.e., drone) (Bednarik and Tukiainen 2006). This duration was calculated based on a C# script, which provided timestamps of instances when users were looking at the drone and not on their task. More specifically, and using the collected gaze timestamps, each fixation duration was obtained by deducting the last instance before the user had shifted their gaze away from the aerial platform, from the first instance the user had looked at the drone. A fixation was only counted if its duration exceeded 100 ms (Bednarik and Tukiainen 2006). Both of these metrics are indicative of distraction and attentional diversion from the task at hand and onto the drone. Upon experiment completion, users were asked, through an open-ended question, to provide their opinion about the VR experiment and the presence of drones on jobsites. Participants' demographics and open-ended feedback were collected using Qualtrics® and data was analyzed in Matlab. This data analysis software was selected due to its accessibility to the research team and its complex data analysis capabilities.

Results and Discussion

Participant Demographics

A total of 44 subjects were recruited to participate in the experiment, assigned randomly and evenly distributed to the Proximal (N=22) and Distal (N=22) drone distance groups. Participants' demographics showed that the subjects from both groups share similar background (Table 1). Overall, recruited participants were split between undergraduate (N=23, 52%) and graduate students (N=21, 48%) and were mostly males (N=34, 77%). More than half were 18 to 24 years old (N=25, 57%) and the majority had less than one year of construction experience (N=27, 61%).

Table 1.

Participant Demographics

Parameter		**Proximal (N=22)**	**Distal (N=22)**
Gender	Male	15 (68%)	19 (86%)
	Female	7 (32%)	3 (14%)
Age	18 to 24 years	14 (64%)	11 (50%)
	25 to 31 years	7 (32%)	7 (32%)

	32 to 38 years	1 (4%)	3 (14%)
	More than 39 years	0 (0%)	1 (4%)
Education Level	Undergraduate	14 (64%)	9 (41%)
	Graduate	8 (36%)	13 (59%)
Construction Experience	0 to 1 year	16 (73%)	11 (50%)
	1 to 5 years	5 (23%)	7 (32%)
	More than 5 years	1 (4%)	4 (18%)

Attentional Impact of Drone on Construction Professionals

Independent samples t-test was performed on the collected participant fixation counts and fixation durations to answer the questions of: (1) whether drones impact construction professionals' attentional state on jobsites, and (2) whether the drone operation distance impact construction professionals' attentional state on jobsites. Obtained results are summarized in Table 2. The analysis showed that users had allocated some of their attention from the task at hand onto the drone at least 14 times, for a total duration of at least 11 s within a 2-minute VR duration. This provides some evidence that the drone has the potential to impact construction professionals' attentional state while accomplishing different construction tasks. The results also show that construction professionals looked at the drone significantly more (i.e., fixation count, $p=0.004$) and for significantly longer durations (fixation durations, $p=0.019$) when the aerial robot was at a distal distance, rather than when being operated at closer distances from them. The data therefore provides evidence that the drone operation distance has impacted construction professionals' attentional states.

Table 2.

Impact of drones on participants' attentional states

Attentional Measures	Proximal Distance Mean ± SD	Distal Distance Mean ± SD	p-value
Fixation Count	13.59 ± 11.19	27.50 ± 17.83	0.004*
Fixation Duration (s)	10.79 ± 9.94	19.40 ± 13.10	0.019*

The results indicate that drones have attracted some of the professionals' attention, and that participants of the proximal distance group looked at the aerial robot less, and for shorter period durations, as opposed to those of the distal distance group. This could be due to the fact that when the aerial robot was at farther distances, participants were not familiar of or able to identify what the drone's intention and role were on jobsites, factors that could prevent them from anticipating the next drone movements and trusting less the aerial robot (Haring et al. 2014; Szafir et al. 2014; Tezza and Andujar 2019). Being at farther distances, participants may perceive the drone as a performance monitoring or surveillance tool. This effect of not being familiar with or able to fully identify what the drone's intention and role were on jobsites may potentially result in participant trusting less the robot, and even provoke higher distraction levels among construction professionals by negatively impacting their perception towards the aerial robot. Additional studies are warranted to investigate the effect of robot intent and role on onsite construction professionals. Participants' responses to the post-experiment open-ended question somehow validated the fact that when users were more knowledgeable and familiar with the robot's role and intent during the experiment, they became more comfortable with its presence, with some subjects indicating that the longer they were exposed to the aerial platform, the more familiar and comfortable they were.

Distraction or attentional diversion has been shown to negatively impact construction professionals' safety performance and potentially result in jobsite injuries and fatalities (Ke et al. 2021). However, determining whether the amount of distraction (as measured by the fixation count and fixation durations caused by drones in this experiment) has practical safety consequences and significance in the real world warrants additional exploration. Additional studies must rely on additional gaze metrics (e.g., on-task and off-task fixations, saccade velocity, saccade amplitude) to measure, with and without drone presence, construction professionals' situation awareness, task attention, and the resulting effect on their safety performance. This ultimately helps in better identifying drones' potential to cause distraction on construction jobsites. In addition, the responses to the open-ended post-experiment question also revealed that almost all the subjects in the proximal distance condition were concerned about the close flying proximity of the aerial robot, indicating that the aerial robot was "loud", made them "nervous", "uncomfortable", "distracted", and "surprised". Such comments were much less common for participants of the distal distance group, who mostly perceived the robot positively, indicating that its presence was "normal", "under control" and that they were not distracted by them. Therefore, future studies should focus on exploring other factors (e.g., robot trust, perceived safety, cognitive load, anxiety) and rely on more construction-specific task performance metrics to fully understand the safety implications associated with human-drone interactions in construction, especially those at close distances.

Conclusion

The goal of this study was to evaluate the attentional costs associated with the presence of drones at different distances from construction professionals on the jobsite. Through a between-subject VR-based experiment, recruited professionals were asked to accomplish a construction task with the presence of an aerial robot at either a proximal or a distal distance while having their eye movements tracked and analyzed. Results showed that drones have an impact on subjects' attentional states, with participants allocating some of their attention onto the aerial robot. The results also revealed that the construction professionals looked at the aerial robot more and for longer durations when operating at farther distances from them. The study findings provide industry personnel and agencies with a better understanding of the attentional risks associated with the presence of drones on jobsites. This ultimately helps in establishing construction-specific drone regulations and ensuring safe interactions between humans and drones in construction.

This study is limited by the nature of the experiment itself, which was conducted in VR. It would be worthwhile to replicate and perform this study within the context of a real construction site; however, safety concerns prevent that from happening at present. In addition, this experiment's participants were asked to perform a relatively simple task of counting the number of trips a worker made across an area of interest in front of them, and were also asked questions about the workplace environment surrounding them. While these questions about their surroundings ensured participants' engagement during the experiment, subsequent studies could attempt to have construction professionals perform more difficult construction tasks, at different levels of human-robot collaborations, and based on other drone distances as defined by Hall (1969) (i.e., 4 ft and 12 ft), and study the resulting impact on their attentional states. Additional studies are also warranted to explore other known risks (i.e., physical and physiological) associated with drone presence on jobsites using other subjective and objective measures to ensure safe human-drone interaction in construction.

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References

Albeaino, G., and M. Gheisari. 2021. "Trends, benefits, and barriers of unmanned aerial systems in the construction industry: a survey study in the United States." *Journal of Information Technology in Construction (ITcon)*, 26: 84–111. https://doi.org/10.36680/j.itcon.2021.006.

Albeaino, G., M. Gheisari, and B. Franz. 2019. "A Systematic Review of Unmanned Aerial Vehicle Application Areas and Technologies in the AEC Domain." *Electronic Journal of Information Technology in Construction*, 24: 381–405.

Bednarik, R., and M. Tukiainen. 2006. "An eye-tracking methodology for characterizing program comprehension processes." *Proceedings of the 2006 symposium on Eye tracking research & applications*. San Diego, California: Association for Computing Machinery.

Cohen, J., C. LaRue, and H. H. Cohen. 2017. "Attention interrupted: Cognitive distraction & workplace safety." *Professional Safety*, 62 (11): 28–34. OnePetro.

Davila Delgado, M., L. Oyedele, A. Ajayi, L. Akanbi, O. Akinadé, M. Bilal, and H. Owolabi. 2019. "Robotics and automated systems in construction: Understanding industry-specific challenges for adoption." *Journal of Building Engineering*, 26: 100868. https://doi.org/10.1016/j.jobe.2019.100868.

Goessens, S., C. Mueller, and P. Latteur. 2018. "Feasibility study for drone-based masonry construction of real-scale structures." *Automation in Construction*, 94: 458–480. https://doi.org/10.1016/j.autcon.2018.06.015.

González-deSantos, L. M., J. Martínez-Sánchez, H. González-Jorge, F. Navarro-Medina, and P. Arias. 2020. "UAV payload with collision mitigation for contact inspection." *Automation in Construction*, 115: 103200. https://doi.org/10.1016/j.autcon.2020.103200.

Hall, E. T. 1969. "Distances In Man." *The Hidden Dimension*. New York, NY, USA: Anchor Books.

Hallowell, M. R., and J. A. Gambatese. 2009. "Activity-Based Safety Risk Quantification for Concrete Formwork Construction." *Journal of Construction Engineering and Management*, 135 (10): 990–998. American Society of Civil Engineers. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000071.

Haring, K. S., Y. Matsumoto, and K. Watanabe. 2014. "Perception and Trust Towards a Lifelike Android Robot in Japan." *Transactions on Engineering Technologies*, H. K. Kim, S.-I. Ao, and M. A. Amouzegar, eds., 485–497. Dordrecht: Springer Netherlands.

Holmqvist, K., M. Nyström, R. Andersson, R. Dewhurst, H. Jarodzka, and J. Van de Weijer. 2011. *Eye tracking: A comprehensive guide to methods and measures*. OUP Oxford.

Ibrahim, A., and M. Golparvar-Fard. 2019. *4D BIM Based Optimal Flight Planning for Construction Monitoring Applications Using Camera-Equipped UAVs*. 224.

Javaid, M., I. Haleem Khan, R. Singh, S. Rab, and R. Suman. 2021. "Exploring contributions of drones towards Industry 4.0." *Industrial Robot: the international journal of robotics research and application*, ahead-of-print. https://doi.org/10.1108/IR-09-2021-0203.

Jeelani, I., and M. Gheisari. 2021. "Safety challenges of UAV integration in construction: Conceptual analysis and future research roadmap." *Safety Science*, 144: 105473. https://doi.org/10.1016/j.ssci.2021.105473.

Jiang, W., Y. Zhou, L. Ding, C. Zhou, and X. Ning. 2020. "UAV-based 3D reconstruction for hoist site mapping and layout planning in petrochemical construction." *Automation in Construction*, 113: 103137. https://doi.org/10.1016/j.autcon.2020.103137.

Kang, Y., S. Siddiqui, S. J. Suk, S. Chi, and C. Kim. 2017. "Trends of Fall Accidents in the U.S. Construction Industry." *Journal of Construction Engineering and Management*, 143 (8):

04017043. American Society of Civil Engineers. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001332.

Ke, J., M. Zhang, X. Luo, and J. Chen. 2021. “Monitoring distraction of construction workers caused by noise using a wearable Electroencephalography (EEG) device.” *Automation in Construction*, 125: 103598. https://doi.org/10.1016/j.autcon.2021.103598.

Lipscomb, H. J., J. E. Glazner, J. Bondy, K. Guarini, and D. Lezotte. 2006. “Injuries from slips and trips in construction.” *Applied ergonomics*, 37 (3): 267–274. Elsevier.

Martinez, J. G., G. Albeaino, M. Gheisari, R. R. A. Issa, and L. F. Alarcón. 2021. “iSafeUAS: An unmanned aerial system for construction safety inspection.” *Automation in Construction*, 125: 103595. https://doi.org/10.1016/j.autcon.2021.103595.

Mendes, E., G. Albeaino, P. Brophy, M. Gheisari, and I. Jeelani. 2022. “Working Safely with Drones: A Virtual Training Strategy for Workers on Heights.” *Construction Research Congress 2022*, 622–630.

Mutis, I., and A. F. Romero. 2019. “Thermal Performance Assessment of Curtain Walls of Fully Operational Buildings Using Infrared Thermography and Unmanned Aerial Vehicles.” *Advances in Informatics and Computing in Civil and Construction Engineering*, I. Mutis and T. Hartmann, eds., 703–709. Cham: Springer International Publishing.

Nadhim, E. A., C. Hon, B. Xia, I. Stewart, and D. Fang. 2016. “Falls from Height in the Construction Industry: A Critical Review of the Scientific Literature.” *Int J Environ Res Public Health*, 13 (7). https://doi.org/10.3390/ijerph13070638.

Namian, M., A. Albert, and J. Feng. 2018. “Effect of distraction on hazard recognition and safety risk perception.” *Journal of construction engineering and management*, 144 (4): 04018008. American Society of Civil Engineers.

Namian, M., M. Khalid, G. Wang, and Y. Turkan. 2021. “Revealing Safety Risks of Unmanned Aerial Vehicles in Construction.” *Transportation Research Record*, 2675 (11): 334–347. SAGE Publications Inc. https://doi.org/10.1177/03611981211017134.

Rozenfeld, O., R. Sacks, Y. Rosenfeld, and H. Baum. 2010. “Construction Job Safety Analysis.” *Safety Science*, 48 (4): 491–498. https://doi.org/10.1016/j.ssci.2009.12.017.

Siebert, S., and J. Teizer. 2014. “Mobile 3D mapping for surveying earthwork projects using an Unmanned Aerial Vehicle (UAV) system.” *Automation in Construction*, 41: 1–14. https://doi.org/10.1016/j.autcon.2014.01.004.

Szafir, D., B. Mutlu, and T. Fong. 2014. “Communication of Intent in Assistive Free Flyers.” *Proceedings of the 2014 ACM/IEEE International Conference on Human-Robot Interaction*, HRI ’14, 358–365. New York, NY, USA: Association for Computing Machinery.

Tezza, D., and M. Andujar. 2019. “The State-of-the-Art of Human–Drone Interaction: A Survey.” *IEEE Access*, 7: 167438–167454. https://doi.org/10.1109/ACCESS.2019.2953900.

Xu, Y., and Y. Turkan. 2022. “The development of a safety assessment model for using Unmanned aerial systems (UAS) in construction.” *Safety Science*, 155: 105893. https://doi.org/10.1016/j.ssci.2022.105893.

Zhang, K., P. Chermprayong, F. Xiao, D. Tzoumanikas, B. Dams, S. Kay, B. B. Kocer, A. Burns, L. Orr, C. Choi, D. D. Darekar, W. Li, S. Hirschmann, V. Soana, S. A. Ngah, S. Sareh, A. Choubey, L. Margheri, V. M. Pawar, R. J. Ball, C. Williams, P. Shepherd, S. Leutenegger, R. Stuart-Smith, and M. Kovac. 2022. “Aerial additive manufacturing with multiple autonomous robots.” *Nature*, 609 (7928): 709–717. https://doi.org/10.1038/s41586-022-04988-4.

Zhou, Z., J. Irizarry, and Y. Lu. 2018. “A Multidimensional Framework for Unmanned Aerial System Applications in Construction Project Management.” *Journal of Management in Engineering*, 34 (3): 04018004. American Society of Civil Engineers. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000597.

Project and Construction Management Certification

The construction industry accounts for greater than one-tenth of the global Gross Domestic Product (GDP). Evolving sophistication and demands of clients and changes to laws and regulations profoundly impact the environment and dynamics of this enormous sector. To deal with modifications, the construction industry is bringing changes to the construction methods and practices by formalizing the project management approach using specialized methodologies. Construction professionals enroll in construction and project management certification programs to stay current with industry processes and practices. Numerous organizations, institutions, and associations offer various types of construction and project management certification. In this paper, the certification programs of Associated General Contractors of America (AGC), Associated Builders and Contractors (ABC), National Center for Construction Education and Research (NCCER), The Institute of Project Management, American Institute of Constructors (AIC), Construction Management Association of America (CMAA), Project Management Institute (PMI) and International Project Management Association (IPMA) are evaluated. This research provides accurate and updated information on the types of certifications, eligibility criteria, exam formats, cost, validity, and renewal process of the project and construction management certifications offered by certification bodies recognized by the construction industry in the United States.

Keywords: Construction Management, Project Management, Training, Certification, Accreditation

Introduction

Construction, which includes buildings, infrastructure, and industrial structures, is the world's most important industry, accounting for 13% of the global Gross Domestic Product (GDP) (McKinsey and Company, 2020). Customer demand alterations and changes to laws and regulations profoundly impact the environment and dynamics of this sector. The customer demand and market rules and regulations, such as cost pressure with limited funding and affordable housing concerns, large-scale and complex projects, increased limitation on work-site sustainability and safety, and evolving sophistication and needs of clients, drastically alter the characteristics of the construction projects (Remer & Ross, 2014). To meet demand, the construction industry is making adjustments and bringing improvements to the processes and dynamics of construction methods and practices by formalizing the project management approach using specialized methodologies (Soroka-Potrzebna, 2021). Hence, construction and project management competencies and skills are becoming more and more significant (Aslam & Bilal, 2021). To build necessary capabilities, construction professionals have increasingly enrolled in construction and project management certification programs (Remer & Ross, 2014).

Professional certification is the process of providing written assurance that an individual conforms to specified requirements or standards for professional competence (Remer & Ross, 2014). Professional certification typically requires some level of professional experience. Certification is earned by passing one or more exams developed by an organization or association that implements the prescribed industry standard. To maintain their credentials, individuals must be involved in profession or professional development and fulfilling the requirements. In short, the certification confirms that the person has passed an appropriate exam that ensures the individual meets industry standards (Remer & Ross, 2014).

Certification was common for technicians and craftworkers in the past. Currently, voluntary/specialty certifications are gaining popularity among engineers and practitioners (Blomquist et al., 2018). In the United States, many firms and agencies are considering certifications as one of their selection criteria for their construction and project managers (Farashah et al., 2019). Numerous organizations, institutions, and associations offer various types of construction and project management certification. This research aims to provide accurate and updated information on voluntary project and construction management certifications for individuals offered by certification bodies accredited by an authoritative organization to ensure that their certification meets international standards and updated practices of the construction industry.

Methodology

For this study, a literature review was conducted to investigate the project and construction management certifications recognized and highly valued by the construction industry in the United States. The literature search was performed using the keyword strategy. The words 'certification', 'construction management,' 'project management', 'engineering management', and 'management training' were searched in web sources such as Web of Science, Google Scholar, and Scopus. All relevant publications have been downloaded and carefully reviewed. Key terms in the certification process are defined as follows:

- Certification— the process by which a certification body assesses and acknowledges the fulfillment of established quality standards and usually grants certain privileges to the certification holder (Vlasceanu et al., 2007).
- Certification Body— the association, institution, organization, or agency performing the certification process.
- Accreditation— the process by which an accreditation body assesses and evaluates the quality certification program to formally recognize it as satisfying specific minimum requirements or standards (Vlasceanu et al., 2007).
- Accreditation Body— the authoritative governmental or non-governmental body performing the accreditation process.

In this study, the project and construction management certifications are reviewed. Figure 1 shows the research methodology.

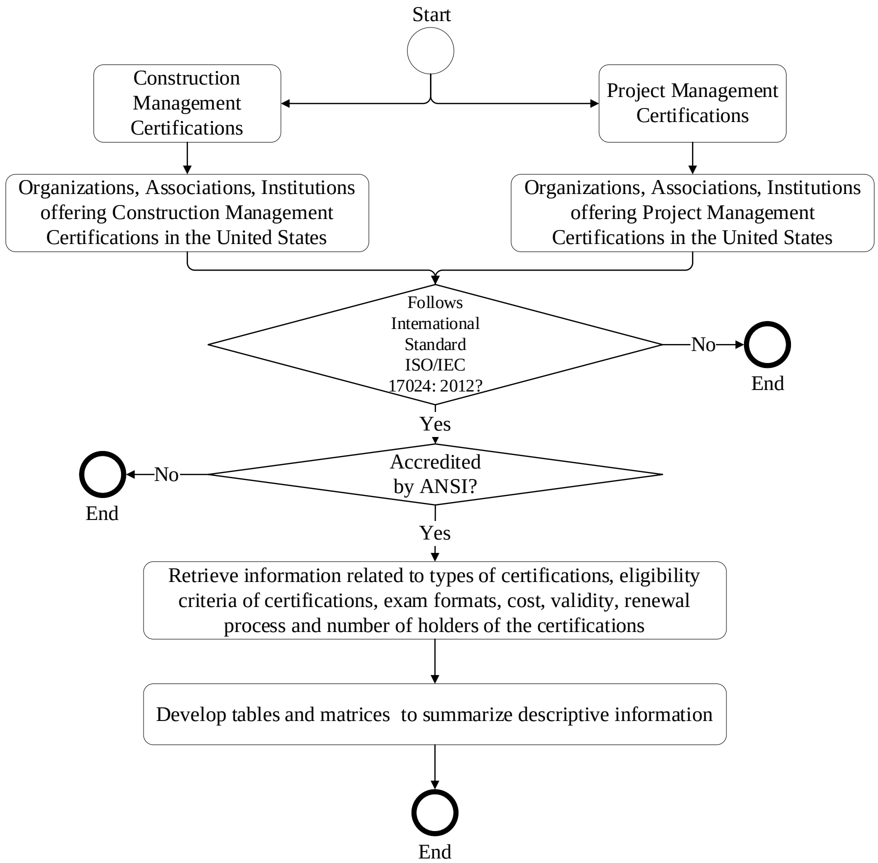

Figure 1. Research Methodology

The International Electrotechnical Commission (IEC) and the International Organization for Standardization (ISO) collaborate to create a specialized system for worldwide standardization (ISO, 2022). The ISO and IEC establish technical committees, and member countries participate in particular fields of technical activity, developing international standards (ISO, 2022). The International Standard ISO/IEC 17204:2012 (Conformity assessment — General requirements for bodies operating certification of persons) has established internationally accepted guidelines that provide the basis for the recognition of the certification bodies and individual certification process (ISO, 2022). The International Standard ISO/IEC 17204:2012 contains principles, guidelines, and requirements for the development of the professional certification process (ISO, 2022). In this study, International Standard ISO/IEC 17024: 2012 was selected as the first gateway for the certification process of the certification bodies evaluated. The International Standard serves as a criterion for the recognition and national and global acceptance of a certification process.

Accreditation bodies in the United States, such as the Council of Engineering and Scientific Specialty Boards (CESB), accredit certification programs that entities offer. CESB accredits programs seeking accreditation based on its own standards and guidelines and does not accredit under ISO/IEC 17024 (CESB, 2022). The National Commission for Certifying Agencies (NCCA) is another accreditation body certifying the programs conforming to the NCCA standards. NCCA also does not accredit the ISO/IEC 17024 requirements but has its own standards. The American National Standard Institute (ANSI) has accredited certification programs since 1970. ANSI is a member of the International Accreditation Forum (IAF) (ANSI, 2022). The United State government highly relies on ANSI accreditation to assess the quality of certification programs offered by certification bodies (ANSI, 2022). The ANSI accreditation board provides an accreditation process that improves industry practices and differentiates the quality certification program (ANSI, 2022). ANSI accredits the certification bodies under ISO/IEC 17204. While several other accreditation bodies exist, ANSI is highly respected worldwide (ANSI, 2022). ANSI, the most highly recognized accreditation body in the United States, has been considered the second gateway for the certifications evaluated in this research. ANSI accreditation provides increased value, reliable examinations, broader global recognition, greater security, increased professionalism, third-party evaluation, and test development benefits to the certification process (CMAA, 2022).

Considering the criteria mentioned above, construction and project management certification were examined. The certifications satisfying both criteria were further investigated. Tables have been created to summarize descriptive information on eligibility criteria, exam formats, cost, validity, and renewal process of the certifications to update the knowledge of professionals and practitioners in the field.

Literature Review

A literature review was conducted to investigate organizations offering construction and project management certifications in the United States. The organizations and their certifications are discussed below:

Associated General Contractors of America (AGC). In its mission statement, the AGC describes itself as "the voice of the construction industry." With more than 27,000 member firms and 89 chapters, AGC of America is the leading organization for the construction sector (AGC, 2022). AGC of America offers various educational programs designed to improve individual career options and the performance of construction companies and the industry. In project and construction management, AGC of America offers nationally recognized Certification of Management-Lean Construction (CM-Lean (AGC, 2022)). CM-Lean does not follow ISO/IEC 17024 and is not accredited by ANSI; therefore, it is not included in the list for further investigation.

Associated Builders and Contractors (ABC). *With* the voice of merit shop as its slogan, the Associated Builders and Contractors is a nationwide trade group for the construction industry with more than 21,000 members. The 69 chapters of ABC assist members in developing expertise to deliver the projects in a safe, proper, and profitable manner (ABC, 2022). The Project Management Institute of the ABC offers an 80-hour project and construction management course divided into two 40-hour sessions. The break between two sessions is for practical work and reporting (ABC, 2022). The ABC program and courses do not follow ISO standards and are not ANSI accredited. Hence, they were not further investigated.

National Center for Construction Education and Research (NCCER). NCCER works toward building a safe, productive, and sustainable workforce. NCCER is a recognized organization by the private and public sectors for the training and certification of construction practitioners. The certification and accreditation of NCCER are primarily focused on technicians, operators, and craftsmanship (NCCER, 2022). NCCER offers Management Learning Series to provide qualified management professionals to the industry. Fundamentals of Crew Leadership, Project Supervision, and Project Management are important construction and project management programs offered by

NCCER (NCCER, 2022). The teaching series of NCCER is not ANSI certified. Therefore, it falls beyond the scope of this study, and it is not examined any further.

The Institute of Project Management. The Institute of Project Management is the only internationally recognized certification authority that offers project management certification, training, and postgraduate opportunities (IPM, 2022). The Institute of Project Management is the official evaluator and issuing authority for Certified Project Office (CPO), Certified Project Professional (CPP), Certified Project Master (CPM), and Certified Project Director (CPD). Although some certifications require renewal every few years, The Institute of Project Management certifications is lifetime certifications awarded without conditions (IPM, 2022). The Australian government accredits the Institute of Project Management certification, and it does not follow the rigorous requirement of ANSI specified for further investigation in this research.

American Institute of Constructors (AIC). American Institute of Constructors promotes professionalism and excellence in construction-related fields. The certifications offered by AIC support professional growth and high-performance standards and provide testing to become a qualified constructor (AIC, 2022). AIC offers Associate Constructor (AC) certification, recently named Certified Associate Constructor (CAC) as the first level certification, and Certified Professional Constructor (CPC) as the highest level of certification in their certification program (AIC, 2022). ANSI has accredited the AC and CPC certification programs under ANAB/ISO/IEC 17024 for personal certification bodies. (AIC, 2022) and (ANSI, 2022). Further information regarding eligibility criteria, exam formats, cost, and validity for AC and CPC is provided in the next section of this paper.

Construction Management Association of America (CMAA). CMAA develops standards for construction project management. CMAA's focus is to provide support for professionals in the field of construction to prepare to succeed regardless of the scale and complexity of the project. (CMAA, 2022). In the CMAA professional development program, the Construction Manager in Training Program (CMIT) and Certified Construction Manager (CCM) are the two certifications offered by CMAA. CMIT is not ANSI accredited. However, CCM certification of CMAA is accredited under ANAB/ISO/IEC 17024 for personal certification bodies by ANSI (CMAA, 2022) and (ANSI, 2022). Further information on CCM certification is provided in the next section.

Project Management Institute (PMI). Project Management Institute is the world's leading authority on project management (PMI, 2022). PMI offers certification for every stage of a person's career. Based on rigorous standards and ongoing research, PMI offers various certifications to help run a project effectively and successfully (PMI, 2022). In the field of construction and project management, PMI offers certifications- PMI Project Management Ready, Certified Associate in Project Manager (CAPM), Project Management Professional (PMP), Program Management Professional (PgMP), Portfolio Management Professional (PfMP) (PMI, 2022). Among all PMI certifications, PMP certification is accredited under ANAB/ISO/IEC 17024 for personal certification bodies by ANSI (ANSI, 2022). Further information on PMP is provided in the next section.

International Project Management Association (IPMA). IPMA develops project management competencies through its 70 member associations. IPMA offers four-level (4LC) competence-based certification processes for individuals, level A, level B, level C, and level D. Level D is an entry-level, and Level A is the highest level of certification. IPMA certification process requires self-assessment to assist the candidate in applying for the most appropriate certification level.

Candidates that meet the qualifications can apply directly for the desired level (IPMA, 2022). All four certifications offered by IPMA follow the ISO standards but are not accredited by ANSI. Hence, it was not further investigated.

Certifications

This section discusses the certifications meeting the criteria of accreditation by ANSI under the International Standards ISO/IEC 17024:2012:

Associate Constructor (AC)

Associate Constructor (AC) is the entry-level certification in the AIC constructor certification program. This level of certification is developed for graduates of a four-year construction program or individuals interested in construction management with four years of Acceptable Professional Experience. Acceptable Professional Experience refers to the experience of managing the execution of construction work. Working in a related profession such as architecture, engineering design, inspection, land surveying, or accounting is not counted as Professional Experience. The last commission meeting changed this certification name to Certified Associate Constructor. For simplicity and familiarity, the name AC is used in this research. AC certification covers ten essential concepts and sections for managing construction processes. Communication skills, engineering management concepts, materials, methods & project modeling, bidding & estimating, budgeting, costs & cost control, planning, scheduling & schedule control, construction safety, construction geomatics, and project administration (AIC, 2022).

The AC exam consists of 300 multiple-choice questions. The exam duration is two 4-hour sessions on a single day. The exam covers ten sections to determine if the applicant has a core competency in construction and is ready to contribute meaningfully to the construction industry. The exam is offered twice yearly (spring and fall) at more than 60 locations across the country (AIC, 2022). Table 1 provides summarized information about the AC certification. The exam is paper-based, computer-based, and administered through university partners or a test center network. The price for the paper-based exam is $165, while the cost for the computer-based exam at partnered universities is $200, and at test centers, it is $235. To help applicants prepare for the AC exam, AIC offers the AC Prep Course for $25 (AIC, 2022). AC certification holders must remain in the construction industry as full-time employees during their tenure as an AC.

Table 1 Associate Constructor Certification Information

Eligibility Criteria	**Exam Format**	**Cost**	**Validity**	**Renewal Process**
Have four-year acceptable experience or education (Ideal for recent graduates of the construction management degree program)	300 multiple choice questions to be completed in two 4-hour sessions	$165 paper-based $200-$235 computer-based	Two years	Continuous work in the construction industry and CPD validated by the supervisor

Certified Professional Constructor (CPC)

Certified Professional Constructor (CPC) is the highest level of certification in the AIC constructor certification program. This level of certification is designed for established constructors with several years of professional experience to take their careers to the next level. Qualifications for CPC Exam are that the individual must have passed or been exempted from AC Level 1 and attain four years of additional Acceptable Professional Experience. The CPC certifications cover nine major subjects and content areas of construction. They are designed to evaluate the applicant's ability to apply recognized principles to solve problems, assess information, and predict outcomes. The covered areas for CPC certification are project scope development, employment practices, working relationships, construction start-up and support, construction resource management, construction cost control, project closeout, construction safety management, and ethics (AIC, 2022).

The CPC exam is composed of 175 multiple-choice questions. The exam duration is a 4-hour session. The exam is divided into nine major subject and content areas testing the applicant's analysis and problem-solving skills. The exam is offered twice yearly (spring and fall) at more than 60 locations across the country. The exam fee for individuals with AC certification is $575, and for non-certified AC is $675. Re-examination costs $500. To help applicants prepare for the CPC exam, AIC offers the CPC Prep Course for $200 for AIC members and $300 for Non-members (AIC, 2022). Table 2 shows summarized information about the CPC certification. AIC offers Continuing Professional Development (CPD) for recertification of CPC. CPD is intended to ensure that certificate holders maintain a high level of expertise throughout their careers. CPC certification holders must earn 32 CPD credits in two years. These credits are classified into two areas- Education (20) or Membership and Service (12) (AIC, 2022).

Table 2 Certified Professional Constructor Certification Information

Eligibility Criteria	**Exam Format**	**Cost**	**Validity**	**Renewal Process**
Completion or Exemption from AC and Four years of Acceptable Professional Experience	175 multiple-choice questions to be completed in one 4-hour session	$575 Current AC and $675 Non-AC	Two years	32 CPD credits hours every 24 months

Certified Construction Manager (CCM)

The Certified Construction Manager (CCM) is a construction and management professional. The purpose of the CCM is to improve the delivery of construction projects with the highest quality and ethical conduct. CCMs provide professional services that involve planning, designing, and constructing a project using effective management approaches. (CMAA, 2022). The CCM certifications cover ten major construction and project management domains- Program/project management, cost management, time management, contract administration, quality management, safety management, risk management, sustainability, technology, and professional practice (CMAA, 2022). Table 3 provides summarized information on the CCM certification.

The eligibility requirement for CCM is a four-year degree in engineering, construction, or architecture-related fields. In addition to a degree, the applicant must have four years of Responsible in Charge (RIC) experience in project supervision, cost control, time and quality management, and contract administration. Applicants with a two-year degree must have four years of experience in addition to four years of RIC experience. Those with no degree must have eight years of experience plus four years of RIC experience. The applicants are required to submit their resumes, project experience documents, and references. The references should validate the applicant's experience. Each application is assessed by the CMAA's Certification Board of Governors (CMAA, 2022).

The exam is 175 multiple choice questions with a 4-hour session to complete. The recertification must be done every three years. The certification office will notify the CCM holder of an upcoming expiration date. The CCM holders are required to submit a Certification Renewal Application to the certification office every three years with earned renewal points information and a renewal fee of $200. 25 Renewal Points are required to maintain certification. These points are earned by involvement in the construction management profession or professional development. The CCM Renewal Handbook describes how to earn CCM renewal points. For example, attending the CMAA conference earns CCM holder 1 Renewal Point. The certification cost is $325 for CMAA members and $425 for non-members (CMAA, 2022).

Table 3 Certified Construction Manager Certification Information

Eligibility Criteria	**Exam Format**	**Cost**	**Validity**	**Renewal Process**
College degree with four years of RIC experience or Two years degree with four years of experience and four years of RIC experience or No degree, eight years of experience, and four years of RIC experience	175 multiple-choice questions to be completed in one 4-hour session	$325 for CMAA members $425 for Non-members	Three years	25 Renewal Points every three years, earned by involvement in profession or professional development and a renewal fee of $200

Project Management Professional (PMP)

PMP is PMI's most popular and internationally recognized certification. A PMP certification indicates that the recipient has sufficient knowledge and experience to perform their duties and complete projects within schedule, budget, and scope constraints. PMP certification covers domains of project initiation, project planning, project execution, project monitoring and control, and project closing (PMI, 2022). Table 4 shows the summary of the PMP certification information.

The prerequisite for PMP certification is a four-year degree and 36 months of leading projects. This does not mean the applicant has the title of the project manager but an experience that falls under any of the five process phases of a project— initiation, planning, execution, monitoring and controlling, and closing. In addition, the applicant must have 35 hours of project management education or a Certified Associate Project Manager (CAPM) certification. If they do not have a bachelor's degree, then a high school diploma or an associate degree (or global equivalent), 60 months of leading projects, and 35 hours of project management education or CAPM Certification. The exam consists of 180 multiple-choice questions, of which five questions are pretest questions and are unscored (PMI, 2022). PMI designed a Continuing Certification Requirements (CCR) Program for maintaining the certifications. Professional Development Units (PDUs) are blocks of one hour spent learning, instructing, or volunteering. The certification holder can maintain their certification by earning PDUs over three years (PMI, 2022). PMP certification is valid for three years and requires 60 PDUs for maintaining certification status.

Table 4 Project Management Professional Certification Information

Eligibility Criteria	Exam Format	Cost	Validity	Renewal Process
A four-year degree, 36 months of leading projects, and 35 hours of project management education or CAPM Certification or A high school diploma or an associate degree (or global equivalent), 60 months of leading projects, and 35 hours of project management education or CAPM Certification	180 multiple choice questions to be completed in 230 minutes	$405 for PMI members $555 for Non-members	Three years	60 PDUs every three year

References

ABC. (2022, April). Retrieved from Associated Builders and Constractors: https://www.abc.org/ABC/

AGC. (2022). Retrieved from Associated General Contractors of America: https://www.agc.org/

AIC. (2022). Retrieved from American Institute of Constructors: https://aic-builds.org/

ANSI. (2022). Retrieved from American Natinal Standard Institute: https://www.ansi.org/about/roles

Aslam, A., & Bilal, A. (2021). Impact of project management certification on project performance. *Journal of Project Management*, *6*(3), 133–142. https://doi.org/10.5267/j.jpm.2021.3.001

Blomquist, T., Farashah, A. D., & Thomas, J. (2018). Feeling good, being good and looking good: Motivations for, and benefits from, project management certification. *International Journal of Project Management*, *36*(3), 498–511. https://doi.org/10.1016/j.ijproman.2017.11.006

CESB. (2022). Retrieved from The Council of Engineering and Scientific Secialty Boards: https://www.cesb.org/about-cesb

CMAA. (2022). Retrieved from Construction Management Association of America: https://www.cmaanet.org/

Farashah, A. D., Thomas, J., & Blomquist, T. (2019). Exploring the value of project management certification in selection and recruiting. *International Journal of Project Management*, *37*(1), 14–26. https://doi.org/10.1016/j.ijproman.2018.09.005

Fordham, P., & Jeanne Martinez. (2005). A VIEW FROM THE BOARD- Certificate vs. Certification. *JOURNAL OF HOSPICE AND PALLIATIVE NURSING*.

IPM. (2022, May). Retrieved from The Institute of Project Management: https://institute.pm/

IPMA. (2022, June). Retrieved from International Project Management Association: https://www.ipma.world/individuals/certification/

ISO. (2022). Retrieved from The International Standard Organization: https://www.iso.org/members.html

McKinsey and Company. (2020). *The next normal in construction.*

NCCER. (2022, June). Retrieved from National Center for Construction Education and Research: https://www.nccer.org/

PMI. (2022). Retrieved from Project Management Institute: https://www.pmi.org/

Remer, D. S., & Ross, E. M. (2014). Review of project and engineering management certifications offered by professional organizations. In *EMJ - Engineering Management*

Vlasceanu, L., Grunberg, L., & Parlea, D. (2007). *Quality Assurance and Accreditation: A Glossary of Basic Terms and Definitions.* Bucharest: UNESCO.

Training about Drone Safety Challenges in Construction using a 360 Virtual Environment: Analyzing Learning Effectiveness

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Utilizing drones on construction sites could put workers who are already in dangerous environments into even more risky situations. Therefore, researchers have explored the safety challenges and their countermeasures regarding drone integration into construction sites. This study proposes using a 360-degree virtual reality (360VR) training environment to educate construction professionals on the safety concerns that drones could pose and how to work safely on a drone-populated site. This study specifically focuses on the knowledge gap of how trainees' backgrounds, such as construction experience, work experience with drones, and prior understanding of drones, could be associated with the effects of the training. This study created comprehensive pedagogical intervention content using 360VR, followed by a user-centered pre- and post-experiment. After training, participants' knowledge levels improved by 41% on average. Furthermore, the results indicate that trainees' construction experience and job experience with drones were not associated with their knowledge levels. Moreover, those with lower levels of understanding about drones significantly improved their knowledge scores after the training. The result shows that trainees with different knowledge about drones may be suitable for trainings with different levels of difficulty.

Key Words: Drones, Safety, 360 Virtual Reality (360VR), Immersive Training, Training Assessment

Introduction

The application of drones, or Unmanned Aerial Vehicles (UAVs), has dramatically grown in the construction industry. This includes project planning, progress monitoring, job site inspection, structural health monitoring, and maintenance assessment (Albeaino et al. 2022b). Using drones in construction brings various advantages, such as the capacity to complete tasks more quickly, safely, and inexpensively (Rachmawati and Kim 2022). However, integrating such flying vehicles on site can also bring new types of safety challenges to workers (Brophy et al. 2022). These safety challenges could generally be categorized as physical risks, attentional costs, and psychological impacts (Jeelani and Gheisari 2021). With these additional concerns, the safety issue in the construction industry, which already accounts for 20% of fatal occupational injuries in the United States (U.S. BLS 2019), might worsen. To address this issue, safety training, in particular, to educate construction workers about the challenges when working with or near drones, has been considered critical to prepare workers for these challenges (Mendes et al. 2022). Previous research has developed 360-degree virtual reality (360VR) safety training and demonstrated the effectiveness of the material (Cheng et al. 2022). With the use of VR technology as a medium, the developed training was able to teach workers in a repeatable, safe, and controlled environment while maintaining a sense of presence on a real construction site populated with drones (Albeaino et al. 2022a). However, the effectiveness of the training materials may vary based on trainees' diverse work experiences with drones and their previous understanding of them. As such, there is a need to explore how work experiences and background knowledge associate with the effectiveness of construction worker-drone safety training. To address this knowledge gap, this study will conduct statistical analyses on the association between workers' professional background and their learning effectiveness in the proposed training.

Application of Drones and their Safety Challenges in Construction

Drones are flying vehicles that can be operated remotely without a pilot and be equipped with onboard sensors, such as cameras, LiDARs, and other devices (Mahajan 2021). Recently, construction-associated operations have become one of the top deployments among all drone applications (Kay Wackwitz et al. 2022). This type of robot is increasingly being utilized in construction to perform various tasks, including earthwork surveying, on-site management, progress monitoring, safety inspection, and damage assessment (Rachmawati and Kim 2022). A recent report also pointed out that 54% of construction respondents to its survey believe that drones will become much more common; 21% of respondents stated that drones will be ubiquitous in the construction industry (DroneDeploy 2022). However, a number of studies have demonstrated that the construction industry is still facing barriers and challenges with legal concerns, technical concerns, weather conditions, and safety concerns regarding the decision to drone adoption (Yahya et al. 2021). Among these concerns, the new safety risks that drones may introduce to construction sites could be the most critical since construction is already dealing with unsatisfactory safety performance. In general, these safety challenges could be classified into three categories: physical risks, attentional costs, and psychological impacts (Jeelani and Gheisari 2021). To address these safety concerns, many countermeasures have been discussed in previous research, including regulatory and administrative interventions, technological interventions, training interventions, and cyber and privacy interventions (Jeelani and Gheisari 2021). Notably, the literature has long stressed on the importance of training interventions in moderating the risks associated with drone integration in construction (Albeaino et al. 2022a). Several researchers have begun to make efforts to develop and evaluate training materials educating construction workers about the safety concerns of working around drones on site (Cheng et al. 2022). Nowadays, more construction companies are adopting drones on job sites, which means some workers may have more experience or knowledge about drones than others. Therefore, there is a need for training with different levels of difficulty to educate workers with different backgrounds. However, limited studies have looked to see whether workers' prior knowledge of and work experience with drones are associated with their learning outcomes. This study proposes a 360VR training regarding the safe integration of drones into construction sites and disseminates it to workers to evaluate how their professional backgrounds would relate to learning outcomes.

VR Application for Construction Safety Training

Given the long-lasting poor safety performance in the construction industry, literature has explored more innovative technologies to remedy this issue. One of the recent trends is to apply VR technology to construction safety training to improve the unengaging and insufficient issues of traditional training (Namian et al. 2016). VR is a technology that involves a computer-generated 3D environment to allow users to explore and navigate contents in the environment (Wen and Gheisari 2021). In contrast to the known defects of traditional safety training, VR-based tools have the advantages of being controllable, repeatable, safe, and capable of exposing users to the actual reality of the industry (Albeaino et al. 2022a). More importantly, this method allows users to gain an immersive experience in simulated hazardous scenarios without exposing construction workers to real risk (Jeelani et al. 2020). With the advancement of VR technology, 360VR, which can provide an immersive experience via popular video-sharing sites (e.g., YouTube©), has grown in popularity in the education and training fields (Snelson and Hsu 2020). Although previous research stated that 360VR cannot provide the same level of immersive experience and interactivity compare to head-mounted VR, its advantage of accecibility has made it be considered to present new opportunities for providing more accessible immersive construction safety education (Pham et al. 2018). Also, previous research shows that the effects on knowledge gain, self-efficacy, and engagement are comparable between 360VR and head-mounted VR (Buttussi and Chittaro 2018). Considering such advantages, a pilot study was conducted to examine 360VR effectiveness for training about drones (Cheng et al. 2022). This study builds on the outcome of that research and provides comprehensive training that also includes the countermeasures to the safety concerns of using drones on construction sites.

Research Methodology

The goal of this study is to develop training that educates construction workers about the safety risks that drones may pose, as well as how to work safely on a drone-populated site in a 360VR environment and to investigate the association between workers' professional backgrounds and learning outcomes. The pedagogical and technological design of the training will be presented, followed by a pre- and post-knowledge evaluation of the recruited construction workers. The following sections will discuss about the development of 360VR training and study metric used for the learning effectiveness assessment. These participants were divided into groups based on their professional backgrounds during the analysis phase, and their learning outcomes were compared between groups using statistical methods to investigate their association.

360VR Training Development

Compared to the previous studies (e.g., Cheng et al. 2022), this paper expanded the safety learning objectives of the training to align with the pedagogical goal. In this section, the 360VR training content development will be illustrated from a pedagogical perspective to demonstrate the different parts and delivery strategies of training, followed by the elaboration of 360VR development from a technical perspective.

Pedagogical Design: Training Content and Delivery Strategies

The pedagogical goal of the training is to equip construction workers with the necessary knowledge about the potential applications of drones on sites, the safety challenges they may introduce, and the countermeasures to address the safety concerns. Along with this pedagogical goal, three learning objectives were identified to ensure trainees can (1) define drones and understand their potential applications in the construction industry; (2) identify the potential safety challenges of drone integration on construction jobsites; and (3) propose possible countermeasures regarding the challenges of safely integrating drones on construction sites. The training content was divided into three parts, and the essential topics that should be covered to achieve the learning objective were listed in Table 1. In this phase, the study metric for learning outcome assessment was also developed coresponding to the three learning objectives of proposed training (examples are provided in Table 1).

Table 1

Learning objectives of proposed training, associated contents and assessment questions

Learning Objective	Training Topics	Examples of Assessment Questions
#1: Trainees can define drones and understand their potential applications in the construction industry	Introduction to drones; Drone definition; Drone applications in construction	What industry is the fastest adopter of drones?
#2: Trainees can identify the potential safety challenges of drone integration on construction jobsites	Physical risks; Attentional costs; Psychological impact	List different ways that drones can cause physical harm to workers on roofs.
#3: Trainees can propose possible countermeasures regarding challenges of safe drone integration on sites	Hierarchy of Control; Closure of training	What are the useful suggestions to address the distraction risk posed by drones?

As the training content was established, different pedagogical delivery methods were applied according to specific training elements (Table 2). First, direct instruction, which is often used in teaching basic concepts (Kim 2014), was adopted with a pedagogical agent explaining conceptual topics in front of a display board. Second, the situated learning method, which allows learners to acquire knowledge in realistic settings (Lave and Wenger 1991), was used to instruct potential hazards. The situated learning scenarios were set as tasks involving roofs, scaffolds, and ladders, representing the riskiest working areas on the jobsite (Samantha Brown et al. 2021). Finally, a “bird’s-eye view” from the viewpoint of drones was presented to demonstrate the applications of drones on site. This strategy can motivate students and provide a better understanding of construction site information (Mutis and Antonenko 2022).

Table 2

Pedagogical delivery strategies

Delivery method	Description	Application Scenarios
Direct instruction	A simulation scenario of the site visit. The pedagogical agent stood in front of a display board on the virtual jobsite and explained the conceptual elements.	Introduction of basic conceptual ideas (e.g., drone definition).
Situated learning	The pedagogical agent used the events that happened in the 360-degree scenes on site to explain related training contents.	Training scenarios that could be simulated in the virtual site (e.g., physical risks)
Bird’s-Eye View	A bird’s-eye view of the virtual site was provided, showing different types of drones and their flight paths as well as various construction-related work on the site.	Demonstrate how drones work on the jobsite (e.g., drone applications)

Technical Design: 360VR Development

Throughout this phase, the Unity© game engine was used to construct a 360VR environment with the essential pedagogical elements to execute the delivery strategies. These elements can be categorized as instructional environment, pedagogical agent, and situated scenarios. 360VR components in the virtual environment were constructed corresponding to these elements, including a virtual construction site, a virtual safety-drone trainer, and the training content-related events (Figure 1). Construction equipment, workers, and drones were organized and animated in the virtual environment to create a drone-dominant site. Then, to develop a pedagogical agent with natural verbal and nonverbal languages, a virtual safety-drone trainer was created using text-to-speech, lip-syncing, and animation technologies. Finally, training content-related events were animated according to the project's pedagogical design.

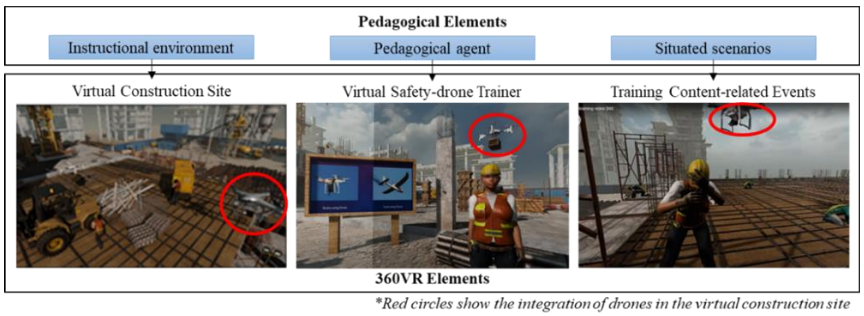

Figure 1 360VR elements correspond to pedagogical elements

Learning effectiveness between different backgrounds

To achieve the research goal of this paper, the survey was aimed at construction workers with varied professional experience and prior knowledge of drones, and the proposed training was delivered via YouTube© to 51 construction workers (39 males and 12 females with average age of 35). The majority of trainees (76%) watched the 360VR training via their laptop or desktop computer. Table 3 provides the demographics of the study participants. In this phase, the participants were divided into different groups according to their professional experience and prior knowledge of drones (Table 3). These group coding was later used for the assessment of result.

Table 3

Group Coding based on construction experience and previous knowledge on drones

Variables	Category	Group Code	Frequency (Percentage)
Experience in the construction industry	<2 years	A0	11 (22%)
	3~4 years	A1	13 (25%)
	Over 4 years	A2	27 (53%)
Work experience on projects using drones	Never	B0	11 (22%)
	1~5 projects	B1	18 (35%)
	6~10 projects or more	B2	22 (43%)
Understanding of drones	Low	C0	11 (22%)
	Medium	C1	22 (43%)
	High	C2	18 (35%)

The participants participated in a pre- and post-knowledge assessment, and the results reveal that after training, participants' knowledge scores significantly improved by 41% on average (from 5.1 to 7.2), indicating the effectiveness of the proposed training material. Furthermore, a one-way ANOVA analysis was performed to evaluate the means of pre- and post-training knowledge scores depending on the diverse professional backgrounds of the participants. As shown in Table 4, there is no significant difference in pre-training knowledge scores between groups with different construction industry experiences; their post-training scores also did not show a significant difference between groups. These results can also be observed when trainees are grouped by their prior work experience with drones. As a result, it is found that prior experience in the construction industry or working on projects involving drones does not result in a different level of knowledge of drone safety in construction either before or after training. In contrast, there is a significant difference in pre-training knowledge scores amongst various groups of people with varying degrees of drone knowledge but no significant difference in post-training knowledge scores. On the other hand, self-reported understanding of drones may actually indicate participants' knowledge level on this topic and therefore cause significant differences in the pre-training scores. However, after training, those groups of participants' knowledge levels can be brought to the same level. Table 5 shows the results of a Tukey HSD (honestly significant difference) test for differences in pre-training means based on the understanding of drones. There are significant differences across all groups of participants, with varying levels of drone understanding.

Table 4

Assessment results based on different professional background

Professional background	Pre-training Mean (SD)			One-way ANOVA		Post-training Mean (SD)			One-way ANOVA	
				F-value	P-value				F-value	P-value
Experience in the construction industry	A0	A1	A2			A0	A1	A2		
	4.9 (2.1)	5.2 (1.3)	5.2 (1.5)	0.182	0.834	6.6 (2.9)	7.7 (1.7)	7.1 (1.5)	0.839	0.438
Work experience on projects using drones	B0	B1	B2			B0	B1	B2		
	5.3 (1.5)	5.1 (1.8)	5.1 (1.5)	0.049	0.952	7.9 (2.1)	6.8 (2.3)	7.0 (1.4)	1.225	0.303
Understanding of drones	C0	C1	C2			C0	C1	C2		
	4.1 (1.1)	5.1 (1.1)	6.7 (1.4)	17.848	<0.01*	6.9 (1.7)	7.1 (2.2)	7.6 (1.8)	0.661	0.521

** P-value < 0.05*

Table 5

Tukey HSD test for differences in pre-training means based on the understanding of drone

Drones understanding levels	Difference of means (SE)	95% CI	P-value
Low vs. High	2.6 (0.4)	(1.55, 3.66)	<0.01*
Low vs. Medium	1.6 (0.4)	(0.55, 2.66)	<0.01*
Medium vs. High	1.0 (0.4)	(0.05, 1.95)	<0.01*

**P-value < 0.05*

The learning outcome assessment results of trainees with different grouping methods are shown in Table 6, and the results of one-way ANOVA are shown in Table 7. The results show that trainees grouped by their construction experience and work experience on projects using drones have increased their knowledge level. However, the increase has no significant differences between groups. Trainees with varying degrees of drone knowledge, in contrast, show differences in learning outcomes, with those with a low and medium level seeing a significant rise in their knowledge scores following training, but those with a high level of understanding did not. Furthermore, the increase in scores among participants with a low level of drone understanding is greater than the increase in scores among those with a medium level of drone understanding, and such an increase brings all trainees up to the same knowledge level as those with a high level of drone understanding. It is found that there is an association between trainees' understanding of drones and their learning outcomes. As such, participants with different knowledge levels of drones may be suited for various training methods. It is suggested that trainees with a higher level of drone understanding could receive a reduced version of the training, while those with a lower level of understanding may benefit more from the training.

Table 6

Learning outcome assessment results of trainees with different grouping methods

Assessment result	Experience in the construction industry			Experience working on projects that used drones			Understanding of drones		
	A0	A1	A2	B0	B1	B2	C0	C1	C2
Pre-training Mean (SD)	4.9 (2.1)	5.2 (1.3)	5.2 (1.5)	5.3 (1.5)	5.1 (1.8)	5.1 (1.5)	4.1 (1.1)	5.1 (1.1)	6.7 (1.4)
Post-training Mean (SD)	6.6 (2.9)	7.7 (1.7)	7.1 (1.5)	7.9 (2.1)	6.8 (2.3)	7.0 (1.4)	6.9 (1.7)	7.1 (2.2)	7.6 (1.8)
P-value	0. 03*	<0.01*	<0.01*	<0.01*	0.02*	<0.01*	<0.01*	<0.01*	0.06

** P-value < 0.05*

Table 7

Learning outcome analysis with trainees' professional backgrounds

Professional background	Learning Outcomes (post-training – pre-training)			One-way ANOVA F-value	One-way ANOVA P-value
Experience in the construction industry	A0	A1	A2	0.568	0.570
	1.8	2.5	1.9		
Work experience on projects using drones	B0	B1	B2	1.022	0.367
	2.6	1.7	1.9		
Understanding of drones	C0	C1	C2	4.668	0.014*
	2.8	2.0	0.9		

** P-value < 0.05*

Conclusion and Future Work

This study proposes a pedagogical intervention in a 360VR environment to educate construction workers on the safety concerns that drones could pose and how to work safely on a drone-populated site. As an increasing number of construction projects started to adopt drone technology on site, some workers started to have more experience with and knowledge of drone applications in construction. Therefore, there is a need to know if workers with various experiences with or knowledge of drones should receive the same safety training. As such, specific analysis was conducted on whether a worker's construction experience, previous experience working with drones, and knowledge of drones could be associated with their learning effectiveness in training. The proposed pedagogical design of the training includes three different aspects related to the safe integration of drones into construction, namely: the introduction of drones into construction; potential safety challenges of drone integration on construction jobsites; and possible countermeasures regarding these challenges. Following the pedagogical design, three different pedagogical delivery strategies were developed to effectively instruct the knowledge, including direct instruction, situated learning, and bird's-eye view. In the technical development phase, three essential elements in the virtual environment were identified, corresponding to three pedagogical elements to complete the design of the 360VR training. A small sample survey with 51 effective data points was conducted to collect trainees' professional backgrounds and evaluate their learning effects with the developed training content. The ANOVA analysis was conducted to understand the learning effects between different groups of trainees with varying construction experience, prior experience working on projects that used drones, and self-reported understanding of drones. The result indicates that there is no association between participants' construction experiences and their learning outcomes; the same result could be found when trainees are grouped by their previous experience of working with drones. In contrast, significant differences in pre-training knowledge levels were found between trainees with varying understanding of drones, and their knowledge levels were brought to the same level as those who had a high drone understanding level afterward. These findings reveal that workers with varying knowledge of drones may receive different levels of safety training on related topics. For example, workers with higher knowledge of drones could learn how to adopt different countermeasures to address the safety challenges posed by drones on site, while those with insufficient knowledge of drones should receive more comprehensive training. On the managerial perspective, it is suggested that training materials targeting trainees with different levels of prior knowledge could be developed to increase their efficacy. Future research could target the development of different levels of training and collect a larger sample of data to understand further how to develop a more effective training strategy regarding the safe integration of drones into construction. Also, this study did not focus on how different devices would influence trainees' learning outcomes and experiences, future studies could also focus on this topic to gain a better understanding of it.

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References

Albeaino, G., P. Brophy, M. Gheisari, R. R. A. Issa, and I. Jeelani. 2022a. "Working with Drones: Design and Development of a Virtual Reality Safety Training Environment for Construction Workers." 1335–1342. ASCE. https://doi.org/10.1061/9780784483893.163.

Albeaino, G., M. Gheisari, and R. R. A. Issa. 2022b. "Human-Drone Interaction (HDI): Opportunities and Considerations in Construction." *Automation and Robotics in the Architecture, Engineering, and Construction Industry*, H. Jebelli, M. Habibnezhad, S. Shayesteh, S. Asadi, and S. Lee, eds., 111–142. Cham: Springer International Publishing.

Brophy, P., G. Albeaino, M. Gheisari, and I. Jeelani. 2022. "New Risks for Workers at Heights: Human-Drone Collaboration Risks in Construction." 321–328. American Society of Civil Engineers. https://doi.org/10.1061/9780784483893.040.

Buttussi, F., and L. Chittaro. 2018. "Effects of Different Types of Virtual Reality Display on Presence and Learning in a Safety Training Scenario." *IEEE Transactions on Visualization and Computer Graphics*, 24 (2): 1063–1076. https://doi.org/10.1109/TVCG.2017.2653117.

Cheng, J.-Y., E. L. S. Mendes, M. Gheisari, and I. Jeelani. 2022. "Construction Worker-Drone Safety Training in a 360 Virtual Reality Environment: A Pilot Study." *EPiC Series in Built Environment*, 19–28. EasyChair.

DroneDeploy. 2022. *State of the Drone Industry Report 2022*.
Jeelani, I., and M. Gheisari. 2021. “Safety challenges of UAV integration in construction: Conceptual analysis and future research roadmap.” *Safety Science*, 144: 105473. https://doi.org/10.1016/j.ssci.2021.105473.
Jeelani, I., K. Han, and A. Albert. 2020. “Development of virtual reality and stereo-panoramic environments for construction safety training.” *Engineering, Construction and Architectural Management*, 27 (8): 1853–1876. Emerald Publishing Limited. https://doi.org/10.1108/ECAM-07-2019-0391.
Kay Wackwitz, Zahra Lotfi, and Hendrik Bödecker. 2022. *Drone Application Report 2022*. Hamburg, Germany: Drone Industry Insights.
Kim, T. 2014. “Direct instruction: An educators’ guide and a plea for action.” *The Behavior Analyst Today*, 6 (2): 111. US: Joseph D. Cautilli. https://doi.org/10.1037/h0100061.
Lave, J., and E. Wenger. 1991. *Situated Learning: Legitimate Peripheral Participation*. Cambridge University Press.
Mahajan, Ar. G. 2021. “Applications of Drone Technology in Construction Industry: A Study 2012-2021.” *International Journal of Engineering and Advanced Technology*, 11: 224–239. https://doi.org/10.35940/ijeat.A3165.1011121.
Mendes, E., G. Albeaino, P. Brophy, M. Gheisari, and I. Jeelani. 2022. “Working Safely with Drones: A Virtual Training Strategy for Workers on Heights.” 622–630. American Society of Civil Engineers. https://doi.org/10.1061/9780784483985.063.
Mutis, I., and P. “Pasha” Antonenko. 2022. “Unmanned aerial vehicles as educational technology systems in construction engineering education.” *Journal of Information Technology in Construction (ITcon)*, 27 (14): 273–289. https://doi.org/10.36680/j.itcon.2022.014.
Namian, M., A. Albert, C. M. Zuluaga, and E. J. Jaselskis. 2016. “Improving Hazard-Recognition Performance and Safety Training Outcomes: Integrating Strategies for Training Transfer.” *Journal of Construction Engineering and Management*, 142 (10): 04016048. American Society of Civil Engineers. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001160.
Pham, H. C., N.-N. Dao, A. Pedro, Q. T. Le, R. Hussain, S. Cho, and C. Park. 2018. “Virtual Field Trip for Mobile Construction Safety Education Using 360-Degree Panoramic Virtual Reality.” *International Journal of Engineering Education*, 34: 1174–1191.
Rachmawati, T. S. N., and S. Kim. 2022. “Unmanned Aerial Vehicles (UAV) Integration with Digital Technologies toward Construction 4.0: A Systematic Literature Review.” *Sustainability*, 14 (9): 5708. Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/su14095708.
Samantha Brown, William Harris, Raina D. Brooks, and Xiuwen Sue Dong. 2021. *Fatal Injury Trends in the Construction Industry*. CPWR–The Center for Construction Research and Training.
Snelson, C., and Y.-C. Hsu. 2020. “Educational 360-Degree Videos in Virtual Reality: a Scoping Review of the Emerging Research.” *TechTrends*, 64 (3): 404–412. https://doi.org/10.1007/s11528-019-00474-3.
U.S. BLS. 2019. “Fatal occupational injuries by event or exposure for all fatal injuries and major private industry sector, all United States, 2019.” Accessed September 20, 2022. https://www.bls.gov/iif/oshwc/cfoi/cftb0334.htm.
Wen, J., and M. Gheisari. 2021. “VR-Electricians: Immersive storytelling for attracting students to the electrical construction industry.” *Advanced Engineering Informatics*, 50: 101411. https://doi.org/10.1016/j.aei.2021.101411.
Yahya, M. Y., W. P. Shun, A. M. Yassin, and R. Omar. 2021. “The Challenges of Drone Application in the Construction Industry.” *Journal of Technology Management and Business*, 8 (1): 20–27.

Why are Irish School-Leavers Pursuing A Higher Education Degree Rather Than Joining A Skilled Trade

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Abstract

The purpose of this research was to investigate the main influences on school-leavers' decision to pursue a career path in the construction industry through either a higher-level degree or a skilled trades program in Ireland. Additionally, this study examined how the key influencers on school-leavers, such as parents, teachers and career counsellors view the construction sector. The research applied a mixed-methods research approach. A survey was conducted among 200 mainly 6th year school-leavers across four secondary schools in the Wicklow and Wexford areas in Ireland. Through a questionnaire data was collected about their reasons for deciding on a higher-level degree compared to a skilled trades program. The influencers' perspective on the construction sector was assessed through semi-structured interviews, enabling triangulation of the data. The findings indicate that most school-leavers were given more information about higher education options than apprenticeship. Furthermore, the research suggests that most school-leavers believed that higher education is considered a superior pathway over joining skilled trades courses. School-leavers see apprenticeships as a lesser achievement than higher education. There is a need to address negative stereotyping associated with apprenticeships and to inform students in secondary school early about the alternative study pathways and career opportunities.

Key Words: Skilled trade, university, apprenticeships, career, Ireland

Introduction

The construction industry in Ireland is experiencing a major skills shortage across a range of crucial construction-related skilled trades, including electricians, carpenters, joiners, pipefitters, scaffolders and many other trades (McNaboe et al., 2019). The primary reasons that may have given rise to this deficiency include an unforeseen increase in the demand for skilled trades and a decrease in the number of students with skilled trades qualifications (McNaboe, et al. 2019). According to the National Skills

Council (2020) an insufficient number of people with skilled trade qualifications have been available to meet the required labour demands. The National Skills Council (2020) also reported that 15% of the vacancies continue to remain unfilled as difficulties persist with successful recruitment for these roles. Aligned with this, registrations for skilled trades and apprenticeship programs have fallen drastically in the past decade to its lowest level in 2010 since the economic recession in Ireland in 2007-2008. Prior to the recession, total new registration for apprenticeship programs in Ireland were consistently more than 8,000 individuals per annum (Ó Murchadha & Murphy, 2016). However, post-recession apprenticeship registrations have fallen dramatically, and construction-related apprentice registration have not exceeded 1,000 applications per annum. (Ó Murchadha & Murphy, 2016).

The purpose of this paper is to investigate the main influences on school-leavers' decision to pursue a career path in the construction industry through either a higher-level degree or a skilled trades course in Ireland.

Analysing the Skills Shortages in the Irish Construction Sector

While 90% of school-leavers in Ireland remain in full-time education after their Leaving Certificate, 65% of each year's cohort progresses onto third-level education (college, university etc) (Mooney, 2021). Registrations into higher education have increased steadily in the past 15 years in Ireland. See figure 1. (CSO, N.D).

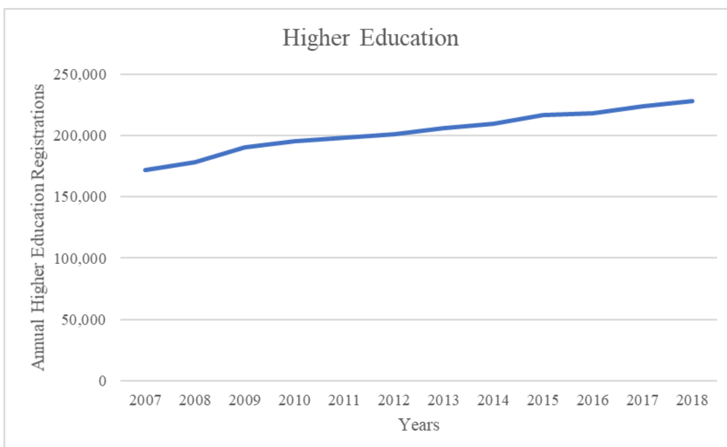

Figure 1. Annual Higher Education Registrations in Ireland (CSO, N.D)

In comparison, registrations for apprenticeship programs have fallen drastically since the economic recession in Ireland in 2007-2008. Total new registration for skilled trades and apprenticeship programs were consistently more than 8,000 individuals per annum prior to the recession (Ó Murchadha & Murphy, 2016). Figure 2 shows a major drop in the construction related apprenticeship registrations post-recession In Ireland which have not exceeded 1,000 applications per year.

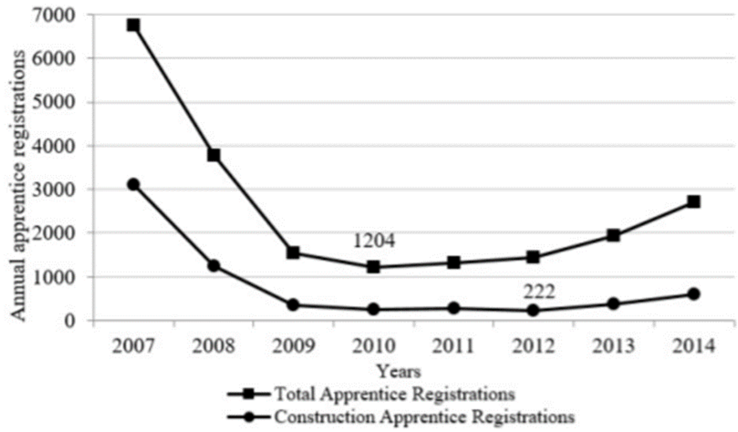

Figure 2. Annual Apprenticeship Registrations in Ireland (Ó Murchadha & Murphy, 2016)

Skills Shortage Effects in Ireland

Richardson (2007) asserts that the term 'shortage' occurs whereby the supply of workers is not sufficient to meet demands. A skills shortage can arise from a variety of reasons and may occur as a result a persistent increase in the demand for particular skills or the reduction in the number of students who are obtaining the relevant qualifications (Richardson, 2007).

In 2015, nearly 50% of all contractors and subcontractors in Ireland encountered a skills shortage (Fitzgerald, 2019). Four years later in 2019, the skills shortage by contractors and subcontractors had increased to 86% according to Fitzgerald (2019). The Central Statistics Office (CSO) in Ireland indicated that many recently qualified apprentices had emigrated abroad (Ó Murchadha and Murphy, 2016). These findings indicate a worrying trend in the skilled workers shortages in Ireland.

In the short term, employers in Ireland have addressed the skills shortage by enticing skilled tradespersons from other European countries to work in construction in Ireland. However, SOLAS, the Irish State Agency for Further Education and Training, highlighted that the lack of available qualified tradespersons may become a significant issue in the long-term for the recovery of the labour market in Ireland (Behan et al., 2015).

School-Leavers Paths Post Leaving Certificate

Mooney (2021) indicates that 65% of each year's school-leavers' cohort progresses onto higher education. Higher education options remain a desired goal for school-leavers in Ireland. The Irish Minister for Further and Higher Education Simon Harris has stated "*I think we should drop the snobby attitude in this country . . . that everyone should be funneled straight from secondary school into university. We're behind the curve in relation to things like apprenticeships*" (O'Brien, 2020). The Irish Times newspaper suggest that apprenticeships are being 'undersold' by secondary schools in Ireland (The Irish Times, 2019).

The Chartered Management Institute (CMI) and EY Foundation in the UK found that 86% of school-leavers had been given information about attending universities, while only 48% of students confirmed to have received information about apprenticeship programs (Miller, 2016). Miller's findings in the UK mirror those in Ireland. Figure 3 shows that the number of school-leavers choosing the higher education option was 53%, which was considerably higher than school-leavers choosing for an apprenticeship program (McCoy et al., 2014).

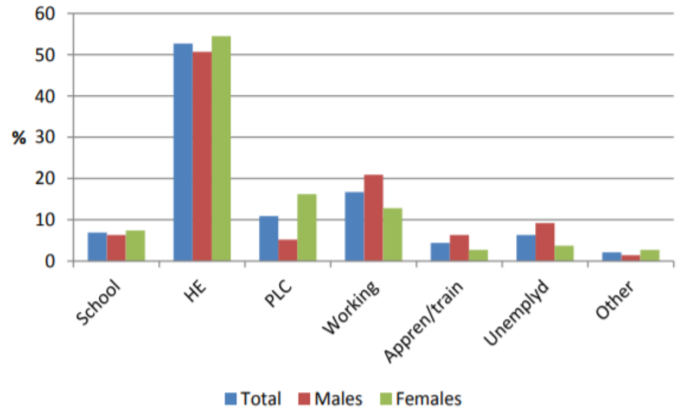

Figure 3. Main Paths for School-Leavers (McCoy et al., 2014)

School-Leavers' Key Influencers when Deciding a Career in Construction

It is important to investigate how school-leavers make their career choices and to assess the key influencers around them. Traditionally, the key influencers include parents, teachers and career advisors (Twumasi et al., 2018). McCoy et al. (2014) reported that school guidance counsellors (83%) are the main source of advice, followed by mothers (73%) and fathers (61%). However, Smyth, Banks and Calvert (2011) contend that parents are the primary source of advice, ahead of school guidance counsellors.

The Construction Industry Training Board (CITB) (2013) suggested that the construction industry as a career choice scored a 6.2 out of 10 by parents while only 5.6 out of 10 by career advisors (Waters and McAlpine, 2016). However, Waters and McAlpine (2016) identified that there is a lack of knowledge about the career opportunities and progression routes in the construction sector among the key influencers. Yet, the roles in the construction industry are often considered to be dirty and not suited for school-leavers who could get into higher education (Waters & McAlpine, 2016)., Clarke and Boyd (2011) also posit that many youths today do not perceive construction trades as a professional, honest or trustworthy career path.

According to Paulsen et al. (2001), parental beliefs have the greatest impact on school-leavers planning for further education. The National House Building Council Foundation (NHCB) in the UK cautioned in 2016 that four in ten parents would discourage young people from entering a building trade (Waters & McAlpine, 2016). This highlights a clear stigma against skilled trades within the construction industry. On the other hand, the Transport Infrastructure Skills Strategy 2016 expresses that parents have an assured stance of construction engineering, which demonstrates that feasibly not all careers within the construction industry are viewed negatively (Waters & McAlpine, 2016).

Career Advisors and Their Influence on School-Leavers

Waters and McAlpine (2016) postulate that the career advisors maintain stereotypical perceptions of the skilled trades in the construction industry, including low pay and hard work. In the UK, a survey published by the CITB (2014) highlighted that 35% of career advisors and teachers view a career in the construction industry as unattractive. Therefore, the career advisors' negative views of skilled trades could prevent school-leavers from entering the construction sector. Furthermore, a survey conducted in Ireland by Dr Róisín Murphy established that only 16% of the apprentices confirmed that guidance teachers steered them towards an apprenticeship program, while 79% of the apprentices asserted that such encouragement did not come from career advisors (Murphy, 2020). In addition, the Association of Colleges (2012) established that 82% of teachers lack the knowledge to advise school-leavers about career opportunities in the construction industry while 44% self-confessed to giving ill-informed advice (CITB, 2014). Conversely, the Educating the Educators report (2012) argues that teachers and career advisors are mindful of the gap in knowledge and have sought assistance to resolve it (Waters & McAlpine, 2016).

Research Methodology

The primary research question of this study was: 'Why are school-leavers pursuing a higher education degree rather than joining a skilled trade in Ireland?' The main objective of this study was to examine the key influences on school-leavers' decision to pursue a career path in the construction industry through either a higher-level degree or a skilled trades program upon their completion of secondary school in Ireland. A mixed methods research method with triangulation was used to increase the validity of the quantitative and qualitative research findings (Dawson, 2019).

School-Leavers Questionnaire

A quantitative research approach was used to collect data from school-leavers. Quantitative research can be conducted through using questionnaires to identify the opinions that people attribute to key events, such as making a career choice (Fellows and Liu, 2008). The quantitative research design was based on a purposive sampling technique by selecting 200 predominantly 6th year (school-leavers) and some 5th year students aged between 16 and 18 years old, across four secondary schools in the Wicklow and Wexford areas in Ireland. The questionnaires comprised of primarily closed-ended questions with pre-populated answer choices for the respondent to choose from, to collect data about their reasons for pursuing a higher-level degree compared to joining a skilled trades program in Ireland. Close-ended responses enable the researcher to collect consistent data (Wolff, 2021). The questions ranged from introductory questions about their school year and gender to more specific questions on career and education influences, the availability of information on career paths and interest in undertaking an apprenticeship. A pilot questionnaire was performed initially to optimize the answer choices. The final question in the questionnaire was an open-ended question to solicit the school-leavers to provide additional feedback in their own words. The questionnaires could be administrated to school-leavers via an online link or a QR code to maximise participant engagement.

Key Influencers Semi Structured Interviews

A qualitative research approach was used to collect data from the key influencers surrounding the school-leavers and their impact on the career choices by school-leavers upon their completion of secondary school in Ireland. The primary key influencers considered for this study comprised the school-leavers' parents, teachers, and career advisors (Twumasi et al., 2018). The perspective of the key influencers on construction related trades was assessed through semi-structured interviews. The primary objective of the semi-structured interviews was to obtain an in-depth opinion from the key influencers about the school-leavers career choices (Dawson, 2019)

Findings and Analysis

The research findings include the results from the interviews with a Head of Apprenticeships, two researchers in the area of apprenticeships, two apprentices and a career guidance teacher as well as the results from the questionnaire completed by 200 5th students and 6th year school-leavers.

Student Survey Summary

The school-leavers indicated that the biggest influence upon deciding their career path after secondary school is their parents (53.5%) ahead of others, friends, and career advisors. The school-leavers also highlighted that following secondary school, 75% were encouraged towards higher education courses, while only 6% of the school-leavers were encouraged towards skilled trades or apprenticeships. This is a similar finding to the number of actual students that progress onto higher education, which is 65% of students as noted by Mooney (2021).

Most school-leavers pointed out that they were given more information about college courses (79%), while only 1% of school-leavers said they received more information about skilled trades or apprenticeship courses. As a result, 69% of school-leavers believed that higher education is considered as the superior pathway for school-leavers and 80% of respondents confirmed they were planning on going to higher education. Only 11% of the school-leavers were considering pursuing a skilled trades or apprenticeship program. Incidentally, 47% of school-leavers would consider entering an apprenticeship program should they fail to get into their chosen higher education course. 80% of the respondents highlighted that the majority of information days were aimed at third-level degree courses. Only 1% of the respondents confirmed that any of the open days were for apprenticeship programs.

Interestingly, 38% of school-leavers believed that a construction related trade was believed to be a viable option and the same percentage believed that it was not a viable option. The remaining 24% said it may be a viable option. 80% of the school-leavers are planning to go to higher education upon completion of secondary school. Only 11% of the school-leavers are considering doing a skilled trades or apprenticeship program after secondary school. Yet, 46% of the school-leavers indicated that they may be more interested in apprenticeship programs, since they are included as a CAO option. 23% of the school-leavers are more interested in apprenticeship programs now that it is a CAO option.
Overall, the school-leavers would rate the attractiveness of construction related trades a 2.93 out of 5. Based on the questionnaire administrated, the school-leavers believe that their influencers would rate construction related trades a 3.02 out of five.

Key Influencers Interviews Summary

The findings from the interviews with key influencers suggest that choosing apprenticeship programs after secondary school might be seen as a failure by school-leavers and would only really be for uneducated people. One key influencer highlighted that *"… apprenticeship is still regarded by many as a pathway for those who just weren't good enough to go to university, which is terrible*". Several key influencers put forward that apprenticeship programs don't receive a positive press and that negative stereotypical images are still associated with these programs. These findings from the interviews correlate with the statistics from Waters and McAlpine (2016) and CITB (2014) which include the low scores that parents and career advisers give the construction industry as a career choice

Similarly, most of the key influencers agreed that skilled trades and apprenticeships programs are being undersold in secondary schools. One key influencer suggested that *"… there is a push for degrees in* *higher education as opposed to apprenticeship programs."* In general, the key influencers concurred that in secondary schools there was a lack of information provided to school-leavers about skilled trades or apprenticeships programs compared to information about higher education options. Miller (2016) established in his study that only 48% of students surveyed received information on apprenticeship programmes.

During conversations about whether career advisors and teachers are aware of the opportunities that apprenticeship programs offer, the findings indicate that the key influencers do not believe the opportunities are being offered as a viable option to school-leavers. Many of the key influencers agreed that career advisers and teachers need to learn more about the potential opportunities that skilled trades and apprenticeship programs can offer to school-leavers. This is in keeping with the findings of Association of Colleges (2012) whereby 82% of teachers lack knowledge on careers in the construction industry. The key influencers believe that the main sources of advice for school-leavers are the career advisers and the parents.

Based on the opinions of the interviewees, guidance counsellors should be the main source of advice about the career path options post-secondary school. However, parents are expected to be a strong influence on the decision-making process. This would suggest that it is crucial to educate parents on the career path options after secondary school.

Apprenticeship programs are frequently associated with the 'old shovel and spade' jobs. One key influencer explained that he went originally through the apprenticeship system himself and hopes to complete a PhD study by summertime. Two other key influencers realised that after two years of college it did not suit them. One other key influencer highlighted that students should receive the correct information about the course options after completing secondary school.

Discussion and Recommendations

If school-leavers continue to refrain from entering the construction industry through skilled trades or apprenticeship programs, there could be significant consequences for the construction industry and ultimately the economic output of Ireland. Options and recommendations are discussed for consideration by the construction industry and the government to address the skills shortage issue.

The research found that school-leavers received very little information about skilled trades and apprenticeship programs and generally students in secondary schools receive more information about higher education course options. However, with limited information available for school-leavers about skilled trades and apprenticeship programs it is apparent that higher education has become the 'superior pathway' and desired goal for school-leavers in Ireland. School-leavers should, and have begun to request adequate information about apprenticeship programs as an equal option to a higher education path. For example, there could be a specific government or sectoral agency that coordinates school visits, talks and open days in secondary schools to inform school-leavers about the apprenticeship options and career opportunities in the construction industry.

More can also be done by the construction industry and government to improve the perception and attractiveness of the construction industry. This can be done by suitably educating parents, teachers and career advisors about the opportunities and the benefits of career paths in the construction industry. More information should be provided to both school-leavers and the key-influencers about skilled trades and apprenticeship programs to avoid these options being 'undersold.' The recent introduction of skilled trades and apprenticeship programs on the CAO system can make a difference in presenting the available options to school-leavers.

In addition, it should be made clear to school-leavers that entering skilled trades and apprenticeship programs does not mean you can't grow any further, but in fact offer excellent career opportunities and subsequent into the construction industry. For example, a school-leaver can start as an apprentice and progress all the way up to level 10 (PhD) on the National Framework of Qualifications in Ireland. In addition, apprenticeships allow school-leavers to learn quickly in a real-life work environment while also earning a wage.

The study concludes that adequate information and benefits should be presented to school-leavers about the study pathways and career opportunities into the construction industry. Furthermore, a better more effective mechanism must be put in place that can benefit school-leavers, apprentices as well as the employers in the construction industry. Lastly, there is a need for a collaborative approach between the industry and government bodies to improve the current state and structure of skilled trades and apprenticeship programs.

References

CITB (2013) Educating the educators. CITB. Available at: https://www.citb.co.uk/media/hmkptzrq/citb-educating-the-educators-key-messaging.pdf.

CSO (N.D) Total Enrolments in Higher Education. Available at: https://hea.ie/statistics/.

Department of Education and Skills (2013) Review of Apprenticeship Training in Ireland. Available at: https://www.gov.ie/en/publication/abb137-review-of-apprenticeship-training-in-ireland/ (Accessed: 10 January 2022).

Eustace, J. (2017) Generation Apprenticeship: Accelerating Real-Life Learning. National Centre for Guidance Education. Available at: https://www.ncge.ie/school-guidance-handbook/generation-apprenticeship-accelerating-real-life-learning (Accessed: 21 November 2021).

McCoy, S. et al. (2014) Leaving School in Ireland: A Longitudinal Study of Post-School Transitions. Dublin: The Economic & Social Research Institute.

McNaboe, J. et al. (2019) National Skills Bulletin 2019. Dublin: SOLAS.

Miller, T. (2016) 'A-level students interested in apprenticeships are being undersold their value, report claims', Construction News, 18 August. Available at: https://www.constructionnews.co.uk/news/knowledge-news/half-of-a-level-students-being-undersold-apprenticeships-18-08-2016/ (Accessed: 16 November 2021).

Mooney, B. (2021) Alternatives to the degree route for school leavers, The Irish Times. Available at: https://www.irishtimes.com/news/education/alternati ves-to-the-degree-route-for-school-leavers-1.4547623 (Accessed: 16 November 2021).

Murphy, D.R. (2020) Apprenticeship Survey 2020. Dublin: CIF. Available at: https://www.tudublin.ie/media/website/news/2021/main-news/CIF-Apprenticeships-Report-2020-.pdf.

National Skills Council (2020) 'Building Future Skills'. Future Skills Needs. Available at: http://skillsireland.ie/all-publications/2020/building-future-skills.html (Accessed: 3 November 2021).

Ó Murchadha, E. and Murphy, R. (2016) ‘Rethinking Apprenticeship Training for the Construction Industry in Ireland’, p. 11.

Paulsen, M. et al. (2001) ‘Going to College: How Social, Economic, and Educational Factors Influence the Decisions Students Make’, The Journal of Higher Education, 72, p. 383. doi:10.2307/2649342.

Smyth, E., Banks, J. and Calvert, E. (2011) From Leaving Certificate to Leaving School: A Longitudinal Study of Sixth Year Students. Dublin: The Liffey Press.

The Irish Times (2019) Obsession with third level a factor in construction worker shortage, The Irish Times. Available at: https://www.irishtimes.com/business/construction/obsession-with-third-level-a-factor-in-construction-worker-shortage-1.3795660 (Accessed: 16 November 2021).

Waters, L. and McAlpine, S.R. (2016) CONSTRUCTION AS A CAREER OF CHOICE FOR YOUNG PEOPLE. CIOB.

Political Consumerism in the Built Environment

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Architectural, engineering, and construction firms design the built environment in a continuing effort to appeal to the home-buying public. Firms' decisions include the exterior finishes that the public see and judge. The main objective of this study was to investigate whether material design elements from the built environment would commonly be perceived to have a political affiliation. Additionally, the study investigated if political consumerism could be seen in respondents' perceptions of the materials when aligned with (or in conflict with) their party. Architectural renderings of the same home with different exteriors (i.e., brick, stucco, or painted wood siding) were presented as experimental stimuli. The study collected data from 584 nationwide respondents. Interestingly, both major parties of Republicans and Democrats identified wood siding as representing their own political party while identifying an alternate exterior finish (usually brick) as representing their opposing party. The political consumerism behavior of reward was uncovered in respondents placing a higher perceived value on the exterior finish with which they identified.

Key Words: Built Environment, Political Consumerism, Exterior Finishes

Introduction

Perhaps at no other time in our history has our nation been so politically divided. The news we watch, the cars we drive, and even the homes we live in seem to project political ideologies (Ordabayeva & Fernandes, 2018; Mercurio & Aiken, 2022). People want to shop for products that provide them with a sense of self-congruence (Duman & Ozgen, 2018). Self-congruence explains how consumers see the brand as similar in their values, behaviors, and self-concepts (Lee, Motion, & Conroy, 2009). Since so many firms and brands are routinely categorized as either Democratic or Republican (Gelb & Sorescu, 2000), could these politically charged consumer behaviors (i.e., rewarding through purchase or punishing through avoidance) be observed based on a building's perceived party affiliation?

Strategic decisions by architecture, engineering, and construction (AEC) firms impact the material selection for the built environment. These decisions are expressed and seen in the design and construction of our built environment. Exterior finishes are part of these design decisions and may have the possibility of being seen as representing a political affiliation. Large commercial buildings are highly complex and consist of multiple exterior design elements that make it challenging to isolate and control for in research. For this reason, this study focuses on residential construction. Utilizing the same experimental home, but with different exterior finishes, allows for the isolation of variables associated with political affiliation.

Political consumerism research has shown that consumers will prefer brands and products that are seen to be copartisan, values-congruent, and sharing their political affiliation (Duman & Ozgen, 2018). This preference extends to consumers both rewarding brands that align with their self-image and punishing brands that are in conflict (Duman & Ozgen, 2018).

The purpose of this work is to investigate whether different building materials, specifically exterior finishes, are interpreted by respondents as having an implicit political affiliation. If exterior finishes are interpreted as having a political affiliation, it presents an opportunity for AEC firms to make more informed decisions during design. Exterior materials seen as in conflict with the local partisan affiliation could be avoided while those materials that are seen as copartisan could be prioritized. Exterior material selection could be used to align with a target customer market drawing on consumer behaviors to reward (or punish) a building based on alignment (or misalignment) with their personal political affiliations. This decision strategy could be utilized to maximize return on investment for future developments.

Literature Review

Political Consumerism

How people vote seems to have a direct relationship to how they shop, where they shop, and the products they purchase (Duman & Ozgen, 2018; Ordabayeva & Fernandes, 2018). Even singular items in our refrigerators popularly project certain political orientations (Keefe, 2020). Political consumers are those who are highly conscious of political and ethical issues and have the motivation to change organizational practices; therefore, political consumers have higher tendencies to express their political identification through consumption behaviors (Sandikci & Ekici, 2009). Consumers not only reward firms that signal parallel political values, but they also tend to punish those firms that do not. This interaction of politics with purchase behavior is the essence of political consumerism. The term political consumerism has been defined as "consumer choice of producers and products based on political or ethical considerations, or both" (Stolle, Hooghe, & Micheletti, 2005, p. 246).

Products are frequently labeled by consumers as either Democratic or Republican (Gelb & Sorescu, 2000. Only recently have researchers uncovered the specific trait adjectives convey political characteristics. Mercurio and Aiken (2022) recently found that adjectives such as Traditional, Conservative, Fiscally Responsible, and Rugged are often deemed more Republican; while Sophisticated, Exciting, and Socially Responsible are traits associated with the Democratic party. Thus, consumers assign political images and appear fully aware of the politicization process. They tend to punish or reward brands because of a perceived association to a particular political ideology (Sandikci & Ekici, 2009). Consumers usually avoid the brands they oppose politically because they believe that those brands "do not have self-congruence, they distract the well-being of the society by polarizing and conservatizing it" (Duman & Ozgen, 2018, p. 475). While this process of political consumerism has been studied for some time (Stolle, Hooghe, & Micheletti, 2005), it has only received limited attention in construction, real estate, and the built environment.

Politics In the Built Environment

Gimpel and Hui (2015) examined respondents' preferences of differing residential properties based on their political affiliations. Respondents were shown four different types of homes ranging from an urban row-house to a two-story rural home. These photos were accompanied by socioeconomic information for the neighborhood. They found respondents favored properties in a neighborhood that aligned with their political party. When researchers later controlled for socioeconomic information, respondents drew upon other differentiating factors, as political “signals” of the properties, to decode and ascribe their political affiliations. Democrat respondents least preferred the two-story home location representing a rural setting, while Republicans least preferred the location closely representing an urban row-house location. The essence of signaling theory is that parties to transactions have differing levels of information; and hence, consumers must make inferences based on what firms (in this case builders) choose to project as informational cues (Kirmani & Rao, 2000; Aiken & Boush, 2006). Potential home buyers evaluate a wide range of signals – from siding to windows, landscaping to entryways.

Partisan alignment with an entire neighborhood has been found to not be the top priority in selecting a home (Mummolo, 2017). Preferences for quality and affordability were primary driving factors. Still, a copartisan neighborhood was found to be an influencing factor. With considerations of copartisan as part of the deciding process, AEC firms have potential to build homes that draw on these preferences to aid in consumers selecting the homes they design and build. That is, AEC firms must clearly understand the signals they are sending as well as how those signals are likely to be interpreted.

While research has been completed on copartisan preference in neighborhood selection, this research expands on this by isolating variables through architectural renderings. Showing survey subjects the same building but with varying exterior materials to see if these materials are interpreted as having a partisan affiliation.

Method

This study utilized a between-subjects experimental design wherein Internet subjects were recruited through an online agency. Hulland and Miller (2018) found that the benefits of recruited Internet samples included reduced costs, quick responses, increased participant diversity, and superior data quality. In this case, assuming that older respondents would be more likely to have home-buying experiences as well as more established political viewpoints, the recruitment of respondents was filtered for being over 30 years old and US citizens. Subjects were exposed to one of three possible conditions (i.e., a brick, a stucco, or a painted wood-siding home rendering).

The survey had three major sections. First, respondents were introduced to the research, told of the survey progression, and asked to imagine they were actively searching for a mid-sized home to purchase. They were asked to provide consent, and then they were exposed to one of the three possible home renderings. All of the renderings were professionally designed by an outside architectural firm and were made to reflect typical sales renderings found online. Upon the firm’s recommendation, the wood-sided house was presented in a neutral light-grey color. Further, in order to increase realism, above the rendering was a sales-oriented paragraph that generically described the home as a “blend of comfort and convenience”, a “tradition of excellence”, “1,840 square feet with 3 bedrooms and 2 baths”, and was said to be “resting in a friendly neighborhood”. The paragraph increased the realism of the online sales-environment, and also served to keep respondents on the page and paying attention to the stimulus.

Section two of the survey began by administering two attention-check questions regarding the home’s door color and exterior. These two questions would later serve to expose respondents who had not properly filled out the survey. Then, 15 semantic differential questions were asked on a sliding scale from 0 – 10. Each adjective pair had anchor points of words antithetical in meaning. The adjectives were derived from the work of Aaker (1997), Valette-Florence et al. (2011), Duman and Ozgen (2018), and Mercurio and Aiken (2022). Finally, respondents were asked to rate the likelihood that the home would sell below, at, or above market average. This question was also administered on the same sliding scale.

Finally, section three of the survey asked questions about political consumerism, political party membership and partisanship, as well as various demographics. Huddy, Mason, and Aaroe's four-item political partisanship scale (2015) utilized 7-point ratings and would help to distinguish levels of connectedness to respondents' parties. The scale yielded a Cronbach's alpha value of 0.905, indicating an excellent level of reliability (George & Mallery, 2003). Accordingly, a new partisanship variable was computed as the sum of the four scale items. Demographics included gender, age groups, education levels, and income.

While 720 respondents were distributed across the survey conditions, a total of 584 provided usable data. Half of the drop in viable respondents were due to the attention check questions (i.e., they did not accurately report the home's siding material). Then, roughly one quarter were due to non-completion, and the remaining quarter were dropped due to inordinately low response times (often with a lack of variance within data). The data set contained 279 women (47.9%), 343 respondents in their 30s (58.7%), and 329 college graduates (56.3%), with the largest income group reporting \$50,000 - \$100,000 annually (n = 239; 40.9%). Lastly, 120 (20.5%) respondents were members of the Republican party, 261 (44.7%) were Democrats, and 199 (34.1%) reported as "Independents".

Results

Using analysis of variance (*ANOVA*) across all three experimental conditions, and evaluating all respondents together, tests yielded ten statistically significant between-group differences. See Appendix A. Wood homes were rated as more Modern, while brick homes were rated as more Traditional. Wood was also rated as more Feminine, and brick was rated as more Masculine. Stucco homes were significantly different from the brick and wood conditions across five negative adjectives (i.e., Boring, Incompetent, Dishonest, Unpatriotic, and lower Market Value). Lastly, the wood-home condition had the highest means relative to three positive adjectives (Exciting, Socially Responsible, and highest Market Value) with high levels of statistical significance. Recall that Mercurio and Aiken (2022) deemed adjectives such as Traditional, Conservative, Fiscally Responsible, and Rugged as Republican; while Sophisticated, Exciting, and Socially Responsible are traits associated with the Democratic party. Thus, latent measures of political trait-adjectives did appear within this foundational study of the built environment.

After isolating respondents by their identified political parties, significant adjective differences were observed. See Tables 1 and 2. First, within the self-identified Republican group, brick homes were perceived as being Masculine, Democrat, and Rugged. Wood homes were found to be Competent and Republican. Stucco was most highly associated with the trait-adjectives of Feminine, Incompetent, and Fragile. Second, focusing analyses on Democrat respondents, results showed nine significant differences by exterior conditions. Brick homes were rated as most Traditional, Masculine, and Rugged. Wood was judged as Modern, Exciting, Feminine, Sophisticated, Competent, Fiscally responsible, Liberal, (prior research would label these as mostly Democratic traits) and projected to be sold at the highest Market Value (out of the three homes). Stucco was associated with being Boring, Simple, Incompetent, Fragile, Conservative, and was projected to be sold at the lowest Market Value.

Additionally, with regards to political partisanship and demographics, *ANOVA* and t-tests yielded other meaningful results. Summed partisanship scores revealed that women indicated higher levels of political partisanship (M_w=15.6; M_m=13.2; t=4.71; p<.01). Moreover, older respondents as well as highly educated respondents were more highly partisan (F=6.13; p<.01; F=3.8; p<.02 respectively). A median-split of each party was then used to group the more highly-identified, partisan respondents from the less politically connected. The highly-partisan Republican respondents rated the brick house as more Democratic (F=5.7; p<.01). The highly-partisan Democrat respondents indicated that wood houses were significantly more Exciting, Feminine, and Liberal (F-values ranged from 3.9 to 9.6; p<.02).

Table 1

Significant Adjectives Ratings by Exterior; ANOVA (Republican Respondents)

Adjective	**Exterior (*n*)‡**	**Mean (*S*)***	**F-statistic**	**P-value**
Feminine – Masculine	Brick (*31*)	5.97 (*1.5*)	2.85	.062
	Stucco (*35*)	5.26 (*1.4*)		
	Wood (*51*)	5.27 (*1.3*)		
Competent – Incompetent	Brick (*32*)	2.94 (*1.7*)	2.78	.066
	Stucco (*36*)	3.31 (*2.1*)		
	Wood (*51*)	2.35 (*1.8*)		
Republican – Democrat	Brick (*32*)	5.03 (*1.3*)	3.11	.048
	Stucco (*35*)	4.63 (*1.1*)		
	Wood (*51*)	4.16 (*1.9*)		
Rugged – Fragile	Brick (*32*)	4.06 (*1.7*)	2.72	.070
	Stucco (*35*)	5.06 (*1.4*)		
	Wood (*52*)	4.52 (*1.9*)		

‡ Subjects exposed to only one of three exterior conditions (Brick, Stucco, or Wood rendering)
* 10-point semantic differential ratings

Table 2

Significant Adjectives Ratings by Exterior; ANOVA (Democrat Respondents)

Adjective	**Exterior (*n*)‡**	**Mean (*S*)***	**F-statistic**	**P-value**
Traditional – Modern	Brick (*94*)	3.34 (*2.0*)	5.97	.003
	Stucco (*82*)	4.01 (*2.4*)		
	Wood (*84*)	4.54 (*2.5*)		
Boring – Exciting	Brick (*93*)	3.34 (*2.1*)	5.83	.003
	Stucco (*80*)	3.03 (*2.1*)		
	Wood (*83*)	4.18 (*2.5*)		
Feminine – Masculine	Brick (*87*)	5.87 (*1.4*)	11.59	<.001
	Stucco (*80*)	5.14 (*1.1*)		
	Wood (*83*)	4.96 (*1.4*)		
Simple – Sophisticated	Brick (*93*)	2.70 (*1.7*)	2.71	.069
	Stucco (*83*)	2.49 (*1.7*)		
	Wood (*84*)	3.15 (*2.2*)		
Competent – Incompetent	Brick (*91*)	3.18 (*1.8*)	2.91	.057

	Stucco (*79*)	3.56 (*1.9*)		
	Wood (*82*)	2.89 (*1.6*)		
Fiscally Responsible	Brick (*91*)	6.09 (*1.5*)	2.60	.076
	Stucco (*79*)	6.00 (*1.8*)		
	Wood (*82*)	6.54 (*1.5*)		
Rugged – Fragile	Brick (*89*)	3.84 (*1.5*)	7.75	<.001
	Stucco (*81*)	4.73 (*1.7*)		
	Wood (*82*)	4.68 (*1.8*)		
Liberal – Conservative	Brick (*93*)	5.66 (*1.5*)	3.60	.029
	Stucco (*81*)	5.85 (*1.5*)		
	Wood (*83*)	5.24 (*1.5*)		
Sold Below Mkt. – Above Mkt.	Brick (*94*)	6.00 (*1.7*)	3.09	.047
	Stucco (*82*)	5.48 (*1.7*)		
	Wood (*83*)	6.04 (*1.5*)		

‡ Subjects exposed to only one of three conditions (Brick, Stucco, or Wood rendering)
* 10-point semantic differential ratings

Discussion

When analyzing results from all respondents in aggregate (Appendix A), the exterior material did not appear to have a direct, easily interpreted, significant party affiliation. There were no explicit differences in means of the rating of "Republican" vs. "Democrat". However, ten significant differences revealed latent differences in people's perceptions of variables deemed political by prior works. Moreover, results did indicate the exterior materials of a home were interpreted as having a political affiliation when grouped according to respondents' party. Democrats interpreted painted wood exterior as Liberal while Republicans interpreted wood exterior as Republican (Table 1 & Table 2). This interesting finding shows that both Democrats and Republicans identify copartisan adjectives to the home with wood siding.

Interestingly, some adjectives were found to be in conflict with respondents' self-image. Republicans associated brick with the trait-adjective Democrat, while Democrats associated Conservative with stucco. Considering that past research has found that Democrats are more likely to punish products that convey different views (Mercurio & Aiken, 2022), this could be a contributing factor in Democrats relegating Republicans to the least-valued stucco homes while Republicans associated Democrats with the middle-valued brick homes. These findings of respondents and their opposing perceptions of building materials are a viable area for further study.

Homes with stucco exteriors were consistently scored unfavorably. Stucco had several lower ratings across all groupings. All three conditions found statistically significant results that stucco was associated with the traits Incompetent, Fragile, and selling for the Lowest Value. Both Democrats and all respondents associated stucco with being Boring. We recognize these findings may be subject to regional preferences for building materials. However, this exploratory study did not control for respondent location. Future research would benefit greatly from including region and predominant construction materials.

The primary goal of this study was to investigate whether design elements of a building would be interpreted as having a political affiliation. Overall, the data suggest that painted wood-siding homes have potential to appeal to both political parties, and thus could be labeled as copartisan. AEC firms would seem to benefit from using wood siding when possible as it was most positively viewed across all respondents. Additionally, stucco's multiple negative associations provides an additional point of consideration for AEC firms to avoid as an exterior finish material.

In conclusion, political consumerism can be measured through trait adjectives and applied to the elements of the built environment. Since consumers are assigning meaningful political associations to homes, AEC firms need to carefully and intentionally choose their building materials.

References & Appendix

Aaker, J. L. (1997). Dimensions of Brand Personality. *Journal of Marketing Research*, *34 (3)*, 347-356.

Aiken, K.D., & Boush, D.M. (2006). Trustmarks, Objective-Source Ratings, and Implied Investments in Advertising: Investigating Online Trust and the Context-Specific Nature of Internet Signals, *34 (3)*, 308-323.

Duman, S., & Ozge, O. (2018). Willingness to Punish and Reward Brands Associated to a Political Ideology. *Journal of Business Research*, *86*, 468-478.

Gelb, B. D., & Sorescu, A. B. (2000). Republican Brands, Democrat Brands. *Journal of Advertising Research*, *40(1)*, 95–102.

George, D., & Mallery, P. (2003). SPSS for Windows step by step: A simple guide and reference. 11.0 update (4th ed.). Boston: Allyn & Bacon.

Gimpel, J. G., & Hui, I. S. (2015). Seeking politically compatible neighbors? The role of neighborhood partisan composition in residential sorting. *Political Geography*, *48*, 130-142.

Huddy, L., Mason, L., & Aarøe, L. (2015). Expressive partisanship: Campaign involvement, political emotion, and partisan identity. *American Political Science Review*, *109(1),* 1-17.

Hulland, J., & Miller, J. (2018). Keep on Turkin. *Journal of the Academy of Marketing Science*, *46(5),* 789-794.

Keefe, J. (2020). Quiz: Can you tell a "Trump" fridge from a "Biden" fridge?. *The New York Times*. Retrieved from https://www.nytimes.com/interactive/2020/10/27/upshot/biden-trump-poll-quiz.html

Kirmani, A., & Rao, A. R. (2000). No Pain, No Gain: A Critical Review of the Literature on Signaling Unobservable Product Quality. *Journal of Marketing 64 (April*): 66-79.

Lee, M., Motion, J. & Conroy, D. (2009). Anti-consumption and Brand Avoidance. *Journal of Business Research*, *62 (2),* 169-180.

Mercurio, K., & Aiken, K.D. (2022). Exploring Political Consumerism and the Emerging Role of Political Brand Personality. *Journal of Brand Strategy*, *11*(2), 1-16.

Mummolo, J., & Nall, C. (2017). Why partisans do not sort: The constraints on political segregation. *The Journal of Politics, 79(1),* 45-59.

Ordabayeva, N., & Fernandes, D. (2018). Better or different? How political ideology shapes preferences for differentiation in the social hierarchy. *Journal of consumer research, 45(2)*, 227-250.

Sandikci, Ö., Ekici, A., (2009). Politically motivated brand rejection. *Journal of Business Research, 62(2)*, 208–217.

Stolle, D., Hooghe, M., & Micheletti, M. (2005). Politics in the supermarket: Political consumerism as a form of political participation. *International political science review, 26(3)*, 245-269.

Valette-Florence, P., Guizani, H., & Merunka, D. (2011). The impact of brand personality and sales promotions on brand equity. *Journal of Business Research, 64(1)*, 24-28.

Appendix A

Adjectives Ratings by Exterior; ANOVA (All Respondents)

Adjective	**Exterior (*n*)‡**	**Mean (*S*)***	**F-statistic**	**P-value**
Traditional – Modern	Brick (*197*)	3.42 (*2.1*)	9.75	<.001
	Stucco (*184*)	4.16 (*2.5*)		
	Wood (*200*)	4.45 (*2.6*)		
Boring – Exciting	Brick (*196*)	3.76 (*2.2*)	11.66	<.001
	Stucco (*183*)	3.30 (*2.3*)		
	Wood (*197*)	4.46 (*2.6*)		
Feminine – Masculine	Brick (189)	5.68 (1.*6*)	11.36	<.001
	Stucco (181)	5.16 (*1.2*)		
	Wood (193)	5.05 (*1.3*)		
Simple – Sophisticated	Brick (196)	2.92 (*1.9*)	10.03	<.001
	Stucco (186)	2.51 (*1.8*)		
	Wood (199)	3.44 (*2.3*)		
Competent – Incompetent	Brick (192)	2.94 (*1.8*)	8.65	<.001
	Stucco (182)	3.58 (*1.9*)		
	Wood (194)	2.85 (*1.8*)		
Honest – Dishonest	Brick (189)	3.31 (*1.6*)	3.85	.022
	Stucco (180)	3.73 (*1.7*)		
	Wood (192)	3.29 (*1.8*)		
Fiscally Responsible	Brick (190)	6.48 (*1.6*)	2.60	.075
	Stucco (180)	6.21 (*1.7*)		
	Wood (195)	6.60 (*1.7*)		
Socially Responsible	Brick (189)	5.85 (*1.7*)	3.88	.021
	Stucco (179)	5.48 (*1.8*)		
	Wood (197)	5.99 (*2.0*)		
Immoral – Moral	Brick (189)	6.48 (*1.8*)	2.42	.090
	Stucco (181)	6.04 (*1.7*)		
	Wood (197)	6.31 (*2.1*)		
Rugged – Fragile	Brick (190)	3.90 (*1.6*)	16.4	<.001
	Stucco (182)	4.82 (*1.5*)		
	Wood (196)	4.58 (*1.7*)		
Republican – Democrat	Brick (190)	4.59 (*1.3*)	.207	.813

	Stucco (179)	4.54 (*1.4*)		
	Wood (193)	4.63 (*1.5*)		
Liberal – Conservative	Brick (192)	5.42 (*1.5*)	1.33	.263
	Stucco (181)	5.57 (*1.6*)		
	Wood (194)	5.34 (*1.3*)		
Unpatriotic – Patriotic	Brick (188)	5.71 (*1.3*)	2.86	.058
	Stucco (174)	5.40 (*1.1*)		
	Wood (193)	5.56 (*1.3*)		
Sold Below Mkt. – Above Mkt.	Brick (196)	5.87 (*1.5*)	6.55	.002
	Stucco (186)	5.43 (*1.6*)		
	Wood (197)	5.94 (*1.5*)		

‡ Subjects exposed to only one of three conditions (Brick, Stucco, or Wood rendering)
* 10-point semantic differential ratings

Analyzing the Safety Risk Factors and Adaptation Measures in Downstream Oil and Gas Industry

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Abstract

Existing risk management practices in Downstream Oil and Gas Industry (DOGI) are ineffective in reducing the frequency of incidents and delays in the turnaround projects. The underestimation of safety risk impacts during the turnaround projects is the root cause of shocking accidents and delays in the DOGI. The paper focuses on analyzing the critical Safety Risk Factors (SRFs) and the potential Risk Adaptation Measures (RAMs) associated with turnaround projects. Current literature was reviewed to explore the complexity of risk management approaches and design a questionnaire survey based on the literature findings. The survey was conducted via online, and the collected data based on 72 samples were analyzed to identify the critical SRFs and the effective RAMs using the relative risk index method. Interviews were conducted with experts to evaluate the survey findings. It is found that SRFs such as fire and explosion hazards are the most critical, followed by slips, trips, and falls; confined space; motor and vehicle accidents and injuries. The study reveals that increasing safety awareness and empowering to key staffs may be an effective way of mitigating the safety risks. The paper concludes that there is strategic difference in risk assessment practices and adopted technology in safety risk mitigations between underdeveloped and developed countries.

Key Words: Oil and gas projects, downstream, safety risk factors, maintenance, and turnaround.

Introduction

Compared to other projects, Oil and Gas Projects (OGPs) are recognized as highly technical projects and complex in nature. And they have a high level of uncertainty, which forces the stakeholders to analyze Safety Risk Factors (SRFs) carefully and adopt appropriate risk management strategies in the projects (Kraidi et al., 2020a). In other words, there are an unidentified number of SRFs, and safety hazards associated with the OGPs due to the volatile nature of the transportation and refining processes of the petrochemical products. However, the stakeholders in OGPs often underestimate or overestimate the SRFs and their impacts on performance, especially turnaround maintenance projects (Karner, 2010).

OGPs are divided into three sectors: upstream, midstream, and downstream. Upstream projects deal with exploration and drilling activities and extracting crude oil and natural gas from the ground. Midstream projects involve the infrastructure and facilities transporting extracted products to the refinery from upstream projects. Downstream includes refinery facilities and linkage to petrol stations and other consuming units (Kraidi, 2020). As shown in figure 1, this paper focuses on the safety risk and the delay in the turnaround maintenance projects in the Downstream of the DOGI.

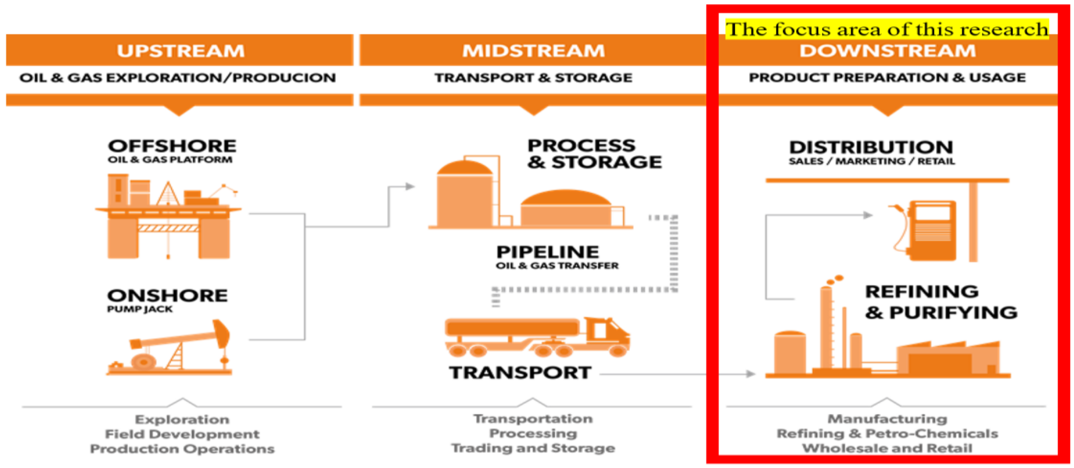

Figure 1. Upstream, midstream, and downstream projects in the oil and gas industry (Kraidi, 2020).

The insufficient and uncertain information about the SRFs and their root causes and the inaccurate estimation of their severity and impact levels on the projects untimely lead to ineffective decision-making during the risk analysis and management processes in DOGI (Aven and Thekdi, 2019). Risk management is driven by uncertainty resulting in time and cost not being estimated effectively, poor specification of project requirements, unforeseen events within the project, and asymmetrical objectives and ground priorities in the projects (Badiru and Osisanya, 2016). Counting, the unpractical maintenance projects in the DOGI sector usually obscure the efficiency and functionality of this industrial sector in different ways, such as shutting the projects down and increasing the cost of the fixing, repairing and replacement work.

Although risks, accidents and failures cannot be avoided entirely in any project, they can be controlled and mitigated by using effective risk management strategies throughout the lifecycle of the projects (Kraidi et al., 2020b). Assessing and ranking the SRFs regarding their degree of influence on a project is significant because dealing with each risk as if it is the most critical one results in substantial losses in terms of resources (Kraidi et al., 2019). Therefore, it is vital to analyze the SRFs in a project accurately, as providing accurate results about the degree of impact of the SRFs enhances the outcomes of the risk management system. Consequently, adequate risk identification and precise risk analysis will enhance the stakeholders' strategies and plan to provide more practical risk adaptation measures in their projects (Bitkowska, 2018).

This paper aims to carefully identify and accurately analyze the RFs associated with OGPs in the turnaround project and suggest the potential Risk Adaptation Measures (RAMs). These measures could be helpful to mitigate the SRFs in the DOGI by evaluating their degree of effectiveness in the projects. The study findings will ultimately help to the decision-makers to identify a sound risk assessment while developing the execution plan for turnaround maintenance projects. The objectives of this paper are:

- To identify the SRFs associated with the turnaround maintenance projects in the downstream sector based on a comprehensive literature review and gain an in-depth understanding of project risk adaptation measures.
- To analyze and rank the SRFs in the DOGI based on their degrees of impact on the projects.
- To enhance the understanding of the RAMs and their effectiveness levels in the DOGI.
- To highlight the crucial difference between SRFs associated with the DOGI in underdeveloped and developed countries.

Literature Review

The oil and gas industry has constantly faced challenges in both developed and underdeveloped countries worldwide. Some of these challenges are caused by the lack of understanding of the SRFs in OGPs (Casa et al., 2009). Furthermore, distributing petrochemical products between upstream and downstream in oil and gas projects is a hazardous process that requires an efficient risk management system. Therefore, the projects in the DOGI are continuously designed, operated, maintained, and managed in a way where risk adaptation is the priority. Besides there are contending views on the effective delivery of turnaround maintenance projects in the DOGI because of the complexity and the cost overruns, which are widespread problems in these projects (Cooper et al., 2005). However, a practical risk adaptation framework could contribute to reducing the project complexity by providing a more insightful understanding of the SRFs and the RAMs and their effectiveness degree in the projects (Kraidi, 2020; Kraidi et al., 2021b).

On the other side, the DOGI requires effective turnaround maintenance, which is “a planned stoppage of production for conducting a comprehensive maintenance of plants and equipment to restore the processes to their original state” (Al-Turki et al., 2019). This is because practical turnaround maintenance projects in DOGI have a success rate of 80% in keeping the refineries operating without shutting down periods (Obiajunwa, 2012). At the same time, an effective turnaround maintenance practice requires proper identification of the SRFs in the projects, as defending a system from an unknown risk is impossible (Kraidi et al., 2021b). Moreover, it requires an accurate assessment and ranking of the SRFs regarding their degree of influence on a project, which is a significant step in the risk management process. Because dealing with each risk as if it is the most critical one results in substantial losses in terms of resources (Kraidi et al., 2019a).

Therefore, this paper conducted an inclusive literature review to identify the SRFs threatening the DOGI comprehensively. As presented in Kraidi (2020) and Kraidi et al. (2021), the literature review has identified but not limited to the following RFs in OGPs.

- **Client risk**. Such as the government relegating RFs; delays in the process and payments; and constant changes in the legations, etc.
- **Contractor risk**. For example, lack of experience; improper training for the staff; execution errors; shortage and low labor productivity and injuries, etc.
- **Planning and feasibility study**. Such as improper project feasibility study; lack of data accuracy and survey information; frequent change of designs; and wrong project cost and schedule estimation, etc.
- **Tendering and contract risk**. Like inadequate tendering; lack of detailed and unclear items; unclear terms and conditions; and poor contract management, etc.
- **Resources and material supply risk**. For example, delays in the delivery of materials to the site; fluctuations in the materials' cost; poor quality of construction materials and shortage of modern equipment, etc.

- **Project management risk**, which could be because of an inappropriate organizational structure; a lack of effective communication and coordination; poor planning and controlling for scheduling, and budgeting; an ineffective quality control; an unclear description of responsibilities and duties of staffs; and difference between the safety cultures of the team, etc.

The literature review has highlighted some of the RAMs in OGPs. Such as increasing safety awareness and authority of the project managers; reducing the complexity of the process; improving communications; changing the existing strategies; improving budget planning; extending the schedule and scope reduction (Kraidi et al., 2021a).

As explained in the rest of the paper, the SRFs and RAMs identified via the literature review were used to design an online questionnaire survey, which was used to analyze the impact of the SRFs and RAMs in the DOGI. The ethical committee board at Liverpool John Moores University has approved the questionnaire survey before distribution. The risk was very minimal, and all the data were protected and dealt with carefully. In addition to the questionnaire survey, interviews from industry expertise were conducted to enhance the understanding and evaluate the survey findings in the DOGI.

Research Methodology

This paper adopted a mixed research methodology that includes qualitative and quantitative risk identification and analysis methods. The SRFs in the DOGI were identified based on current literature review about the potential risks that threaten turnaround maintenance projects in the DOGI. The SRFs and RAMs in the OGPs were identified via the literature review then they have been listed in a questionnaire survey to analyze their probability and severity levels on a five-point Likert scale. The online survey was created using Google Forms and it has been sent to the potential participants via email. The questionnaire survey has been designed in four sections as follows.

- Section I introduced the research topic and the survey's aim to the participants. The participants were also asked about their country of work, occupations, and experience levels.
- Section II highlighted the projects' most common factors and analyzed their probability and severity levels in the DOGI.
- Section III compared the SRFs associated with the turnaround maintenance projects in the DOGI in different locations and countries. Moreover, the survey has tried to understand the difference between RFs and safety standards in developed and underdeveloped countries.
- Section IV focused on evaluating the effectiveness levels of different RAMs that could be used to understand maintenance projects in the DOGI.

The qualitative part of this paper was about enhancing the knowledge and understanding of the RFs and the RAMs in the turnaround maintenance projects in the downstream industry. The interview focused on evaluating the survey results by highlighting the common SRFs in the DOGI and analyzing their levels of impact on the projects. The interviews also focused on the difference between the SRFs in different projects and locations. Finally, the survey tried to evaluate the effectiveness of RAMs that could be used to mitigate the SRFs in the turnaround maintenance projects in the DOGI.

Results

Due to the nature of human observations and responses, surveys may come with a range of errors. Therefore, testing the reliability levels of the data collected from research surveys is important. Keeping the data of the study confidential reduces personal biases during data collection and helps avoid any threats to the reliability and validation levels of the survey (Dzudie, 2013). Cronbach's alpha correlation coefficient (α) has been calculated to assess the reliability level of the questionnaire survey. It measures the average correlation and the internal consistency of the survey items and between the respondents' answers (Cronbach, 1951; Webb et al., 2006). The value of α equals 0.7 means the survey results are above the minimum level of reliability (Prasad et al., 2019). The reliability of the survey was 0.81, which is above the acceptable value of 0.7.

The survey was sent to 130 potential participants, who work in the oil and gas industry. The potential participants were randomly selected and contacted via email, Linked and other social media platforms industry. 72 out of 130 participants have completed the questionnaire survey with a response rate of 55.6%, which is acceptable as per (Kraidi et al., 2021b). Figure 2 below explains the participants' demographic information, which are the country of work, experience, and occupations.

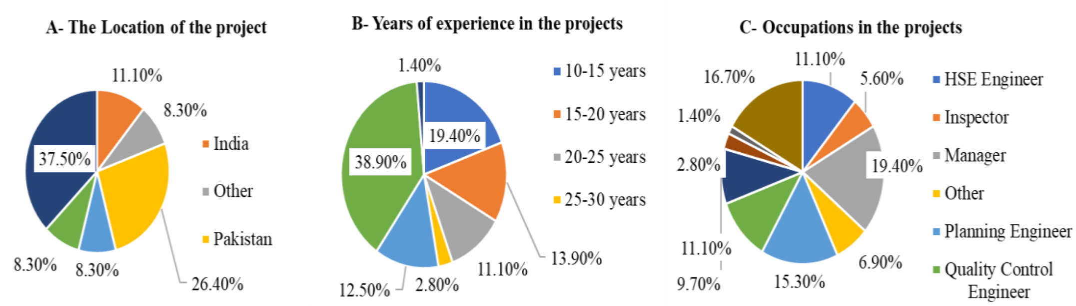

Figure 2. Participants' demographic information: country of work, experience, and occupations.

According to the survey's results, it was found that health and safety-related risks are the most common SRFs in the turnaround maintenance projects in the DOGI. Moreover, the fire and explosion risk under health and safety have the highest probability of threatening the turnaround maintenance projects in the DOGI, followed by slips, trips, and falls; confined space risks; motor vehicle accident risks and injuries; as shown in figure 3 below.

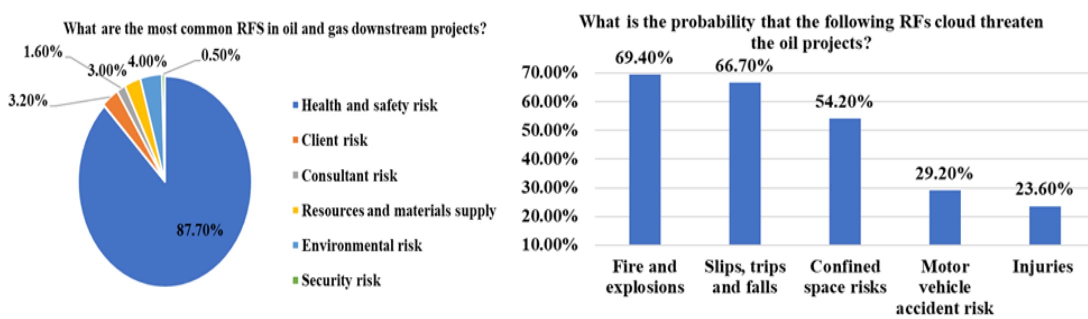

Figure 3. The most common safety risk factors in oil and gas projects and their probability levels.

The impact of the Safety Risk Factors (SRFs) on the projects was evaluated against a six-point Likert scale, as shown in table 1 below. The survey results showed that the fire and explosion-related safety risks are the critical factors with the highest impact on the turnaround projects in the DOGI, followed by slips, trips, and falls; confined space; motor and vehicle accidents and injuries-related RFs, which is lowest impact on the project.

Table 1

The severity levels of the safety risk factor in the oil and gas downstream projects.

Safety Risk Factor (SRFs)	Very high	High	Moderate	Low	Very low	No effect
1. Fire and explosions	55.6%	13.9%	11.1%	5.6%	5.6%	8.3%
2. Slips, trips, and falls	47.2%	20.8%	15.3%	5.6%	9.7%	1.4%
3. Confined space risks	38.9%	22.2%	12.5%	20.8%	4.2%	1.4%
4. Motor & vehicle accidents	9.7%	35.0%	18.0%	19.0%	7.3%	11.0%
5. Injuries	8.0%	5.0%	27.8%	27.2%	6.0%	26.0%

As shown in figure 4 below, where the grey color stands for yes, the SRFs in OGPs vary according to their locations as confirmed by 87.5% of the participants in the survey. Notably, 87% of the participants agreed that OGPs in underdeveloped countries are subjected to different SRFs compared to developed countries. For example, 72.25% of the participants indicated that the downstream projects are subjected to longer shutdown maintenance projects in underdeveloped countries than in developed countries.

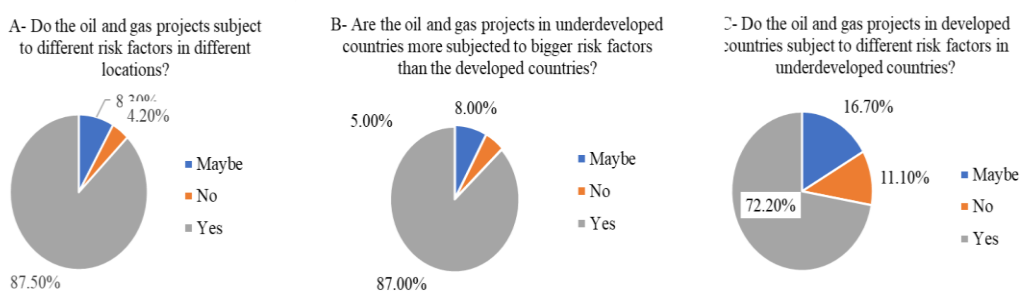

Figure 4. Do the oil and gas projects subject to different safety risk factors in different locations?

It is found that 50% of the participants agreed that OGPs in underdeveloped countries are at higher risk than projects in developed countries. This is because of the lack of infrastructure and safety standards in underdeveloped countries, as 42.7% of the participants said; see figure 5 below.

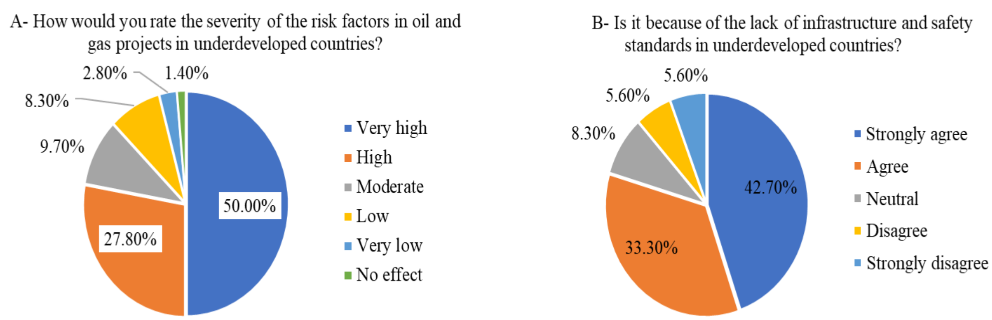

Figure 5. Do the OGDPs in developed and underdeveloped countries subject to different SRFs?

Based on the survey's results, table 2 presents the effective level of proposed risk responses and adaptation measures in turnaround projects in oil and gas industry. It is found that increasing the awareness and authority of the project managers could be one of the most effective RAMs in DOGI, followed by reducing the complexity of the process and improving communications in projects.

Table 2

The effectiveness levels of risk adaptation measures *(RAMs) in oil and gas turnaround projects.*

RAMs	Very high	High	Moderate	Low	Very low	No effect
1. Increasing safety awareness and authorize to PM	39.1%	27.8%	15.3%	15.0%	5.6%	4.2%
2. Reducing the complexity of the process	36.1%	25.0%	11.1%	13.9%	8.3%	5.6%
3. Improve communications	30.6%	36.1%	11.1%	13.9%	4.2%	4.2%
4. Changing the existing strategies	11.1%	16.7%	26.4%	23.6%	19.4%	2.8%
5. Improve budgets planning	5.6%	15.3%	34.7%	19.4%	15.3%	9.7%
6. Extending the schedule	2.83%	11.1%	20.8%	25.0%	31.9%	8.3%
7. Scope reduction	1.4%	4.2%	19.4%	34.7%	29.2%	11.1%
8. Event contingency	5.6%	15.3%	40.3%	22.2%	5.6%	11.1%

This paper conducted two interviews with two experts in oil and gas projects via an online video call. The first interviewee was a lead project engineer with 15 years of experience. And the second was a quality control engineer having 17 years of experience. Both interviewees agreed that poor management; lack of project planning and scheduling; lack of communication, and safety risks are the most common SRFs in the DOGI. On top of installments of necessary equipment, highly flammable substances and confined space are the most critical SRFs in the DOGI. Moreover, both interviewees agreed that the SRFs in the DOGI vary in different locations. In other words, different oil and gas downstream projects are subjected to variable SRFs in different locations. The survey and interview results confirmed that the underdeveloped countries are subjected to diverse the SRFs compared to developed countries because the project's safety standards are different between countries. Therefore, the turnaround projects in the DOGI in underdeveloped countries are more risky in terms of incidents frequency and delay impact than the developed countries. The lesions learning from past accidents in turnaround projects would provide vital knowledge for strategic design, planning and operations turnaround projects and this could be one of the effective ways of risk adaptation measures in the DOGI.

Discussion and Conclusions

The Oil and Gas Projects require the effective risk adaptation strategies to enhance the projects' operations and deliver the turnaround maintenance projects on time and safely. The study findings will enhance the stakeholders' understanding and knowledge about the SRFs and RAMs, which could be helpful to make sound decisions in risk management process in the turnaround projects of the DOGI.

In this paper, the safety risk factors in oil and gas industry were identified based on current and inclusive literature review. Then, the safety risk factors were analyzed and ranked regards impact on the oil industry based on the real experience of whom who have contributed to fill the questionnaire survey that been distributed amongst the stockholders in oil projects. The findings from the industry survey suggested that adequate planning for the turnaround maintenance projects in the Downstream Oil and Gas Industry (DOGI) will enhance the safety of project workers, reduce projects' shutdown periods, and reduce the complexity in the sector. This study highlighted that the highly flammable substances and confined space are the critical SRFs with the highest impact in the DOGI. The study has also suggested that poor planning in the DOGI is one of the critical SRFs that often leads to late deliveries of turnaround maintenance projects. The comparison between the safety risk factors in the oil and gas in both developed and underdeveloped countries may help the stakeholders in developing countries to review their risk management process and enhance health and safety measures via learning from the past projects that were completed successfully in the developed countries.

Additionally, the study reveals that the turnaround projects in underdeveloped countries are subjected to more significant SRFs than the developed countries because of the lack of safety standards and awareness and poor safety training programs for the workers in underdeveloped countries. The SRFs in OGPs were graded in terms of their severity, and it was found that risk levels would be low in the DOGI in developed countries and very high in underdeveloped countries. The study found that increasing the safety awareness and empowering authority of the project manager, reducing the process complexities, and changing the execution strategy are some of the effective RAMs, which could help in minimizing the impacts or the occurrence of the SRFs in the projects. This paper concluded that the critical SRFs associated with the turnaround projects in DOGI vary in nature and impact according to locations of the projects.

Furthermore, the findings of this paper will be used in future research as inputs for life maintenance systems, which will be developed to create effective risk maintenance plans by implementing artificial intelligence and machine learning tools. The small-scale sample of the questionnaire survey limits the results of this study. Hence, it is recommended to include a bigger sample in future research and use real-life case studies to enhance the stakeholders' understanding of the nature and impact of safety risks in turnaround maintenance projects. As well as, to optimize the safety risk management scenarios for OGPs in different locations and countries.

References

Al-Turki, U., Duffuaa, S., Bendaya, M. (2019). Trends in turnaround maintenance planning: a literature review. Journal of Quality in Maintenance Engineering, 25(2), pp. 253–271.
Aven, T., Thekdi, S. (2019). Enterprise Risk Management: Advances on Its Foundation and Practice. Routledge, Taylor and Francis Group, first edition, London and New York, ISBN 978-1-138-38623-5.
Badiru, A., Osisanya, S. (2016). Project management for the oil and gas industry: a world system approach. CRC Press, Taylor and Francis Group, ISBN 13:978-1-4200-9426-8.
Bitkowska, A. (2018). Business Process Management Centre of Excellence as a Source of Knowledge. Business, Management and Education, 16, pp. 121–132.
Casa, B., Simonetti, A., Falco, G., Tonegutti, M. (2009). Italian refiner lowers turnaround maintenance complexity, costs. Oil & Gas Journal, 107(2), p. 48-51.
Cooper, D., Grey, S., Raymond, G.,Walker, P. (2005). Project risk management guidelines managing risk in large projects and complex procurements. John Wiley & Sons, Ltd, ISBN 0-470-02281-7
Cronbach, J. (1951). Coefficient alpha & the internal structure of tests. Psychometrika. 16(3), 297–334.
Dzudie, G. (2013). Effectiveness framework for project management information systems used in United States oil and gas exploration. PhD Thesis, University of Phoenix.
Karner, C. (2010). Consider new coatings for maintenance turnaround: Epoxy system provides speed of application as well as environmental benefits for large storage tanks: Plant design and engineering. Hydrocarbon processing (International ed.), 89(12), pp. 37-38.
Kraidi, L. (2020). Development of an Integrated Risk Management Framework for Oil and Gas Pipeline Projects. PhD Thesis, School of Civil Engineering and Built Environment, LJMU, Liverpool, UK.
Kraidi, L., Shah, R., Matipa, W., and Borthwick, F. (2019). Analyzing the critical risk factors associated with oil and gas pipeline projects in Iraq. Journal of Critical Infrastructure Protection, 24, pp. 14-22.
Kraidi, L., Shah, R., Matipa, W., Borthwick, F. (2020a). Quantitative Analysis of the Delay Factors in

Oil and Gas Pipeline Projects. In Tom Leathem (editor). Associated Schools of Construction Proceedings of the 56th Annual International Conference. Liverpool, UK, 2020, vol 1, pp. 356–363.
Kraidi, L., Shah, R., Matipa, W., Borthwick, F. (2020b). Using stakeholders' judgement and fuzzy logic theory to analyze the risk influencing factors in oil and gas pipeline projects: Case study in Iraq, Stage II. International Journal of Critical Infrastructure Protection, 28, pp. 100337-100346.
Kraidi, L., Shah, R., Matipa, W., & Borthwick, F. (2021a). Analysing Delay Impact from Potential Risk Factors on Project Delivery of Oil and Gas Pipeline: A Case Study in Iraq. Journal of Construction Research, 2(2) pp. 42- 55.
Kraidi, L., Shah, R., Matipa, W., & Borthwick, F. (2021b). An investigation of mitigating the safety and security risks allied with oil and gas pipeline projects. Journal of Pipeline Science and Engineering, 1(3), pp. 349–359.
Obiajunwa, C. (2012). A Best Practice Approach to Manage Workscope in Shutdowns, Turnarounds and Outages. PhD Thesis, Sheffield Hallam University.
Prasad, K., Vasugi, V., Venkatesan, R., Nikhil, B. (2019). Analysis of causes of delay in Indian construction projects and mitigation measures. Journal of Financial Management of Property and Construction, 24(1), pp. 58–78.Webb, N., Shavelson, R., Haertel, E. (2006). 4 Reliability Coefficients and Generalizability Theory. Editor(s): C.R. Rao, S. Sinharay, Handbook of Statistics, Elsevier, (26), pp. 81-124, ISSN 0169-7161, ISBN 9780444521033.

Addressing the Construction Labor Shortage Through Connected Secondary and Post-Secondary Construction Education Pathways: A Descriptive Case Study in Wyoming

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Despite a total population under 600,000, Wyoming's jobs increased by 5,672 positions in 2018. Notably, more than 50% of this job growth was in the construction industry. Until 2019, there were no formal secondary construction education and training programs able to supply the necessary workforce to meet industry needs. Since 2019, Wyoming has been fortunate to build strong construction programs within their high school Career and Technical Education curricula and Community College programs. With the support of the Associated General Contractors of Wyoming, educators at each level have partnered with the University of Wyoming to pilot several collaborative efforts to increase curricular consistency and credit articulation that can culminate in a bachelor's degree in Construction Management. A unique and major focus of the connected secondary to post-secondary construction education program is that it affords students the ability to exit and rejoin the educational pathway while concurrently gaining construction industry experience. This paper describes two programs piloted across educational levels in Wyoming. The use of the Zoom Meetings and Owl Pro technologies worked well to cultivate educational synergy between the classrooms located at each of the institutions across the state. Thus, the findings are helpful to those interested in connecting secondary and post-secondary construction education and training programs to address employment demand.

Key Words: Construction Labor Shortage, College Credit Articulation, Secondary Education, Post-Secondary Education, Skills Training

Introduction and Literature Review

Nearly 91% of more than 1000 US construction firms that responded to a survey distributed by the Associated General Contractors of America (AGC) and Autodesk, report that difficulty in 'finding workers' is driving up construction cost and contributing to project delays (*AGC*, 2022). Wyoming's construction training and education programs, similar to many other states, have been unable to keep pace with the demand and supply the necessary workforce to meet industry needs. Research reveals that the perceived differences between industry practitioners and academia may be a core cause of a current and future training shortfall (Moore et al., 2011). Industry members, training practitioners and educators lay claim to engaging some positive impact on labor supply while occasionally downplaying the efforts of the other groups. It is paramount that all the players in the construction-education space work together in support of providing opportunities to engage, educate and train more people to fill critical positions in the industry. Collaborative engagement is a necessity especially given the Bureau of Labor Statistics prediction of 11% growth in construction-related employment between 2020 and 2030. This prediction should be especially concerning for western US states, in light of the projected high school graduation plateau in 2024, followed by sharp and then steady decline from 2025 to 2030 (Bransberger, 2017).

According to the Research and Planning Office of the Wyoming Department of Workforce Services, employment in Wyoming increased by 5,679 jobs (2.2%) and total payroll increased by $192.1 million

(6.2%) between the first quarters of 2018 and 2019. Construction, which added 2,867 jobs during this period, accounted for nearly half of these job gains. Figure 1 illustrates the positive construction workforce growth and contradicting declining high school graduation between years 2020 and 2030.

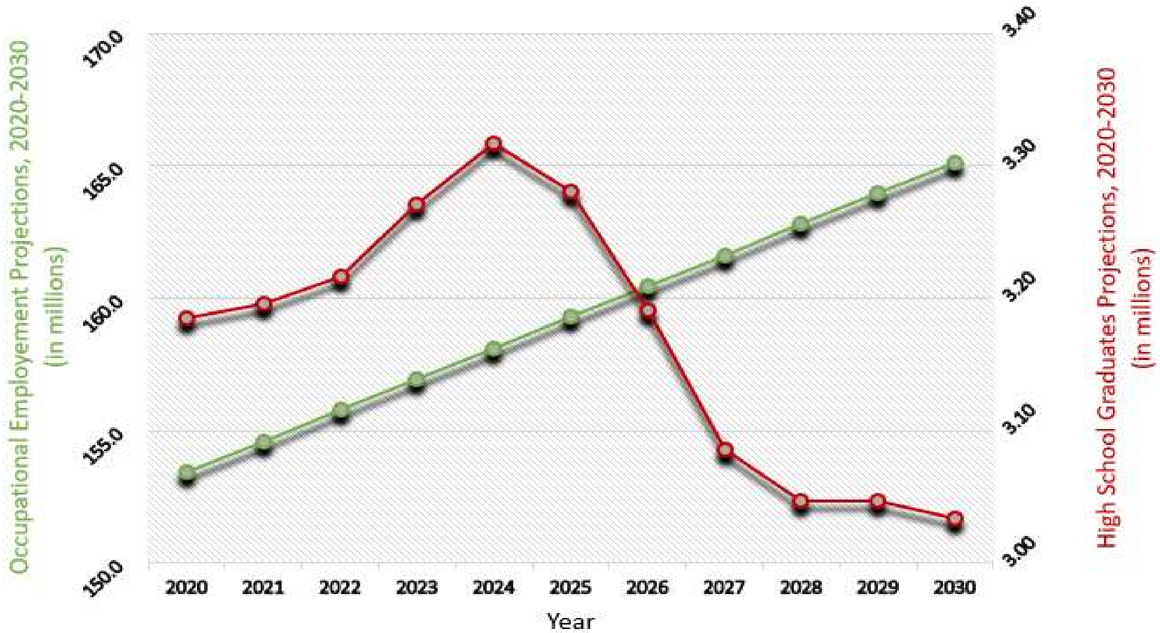

Figure 1. Occupation Growth Versus Anticipated High School Graduation

The positive growth figures recorded and projected for the construction industry require increased efforts to not only maintain but increase the number of individuals entering the construction workforce. Notably, the onset of the COVID 19 pandemic temporarily reversed the observed trajectory with a national decline in all jobs from 162.8 to 153.5 million between 2019 and 2020 (see Figure 2). However, data analysis by the Associated Builders and Contractors show that the construction industry has bounced back faster than the U. S. Bureau of Labor Statistics' (BLS) prediction, with an increase of 311,000 construction jobs nationally between July of 2021 and July of 2022, indicating the ongoing importance of training and recruiting skilled trade's people and construction managers.

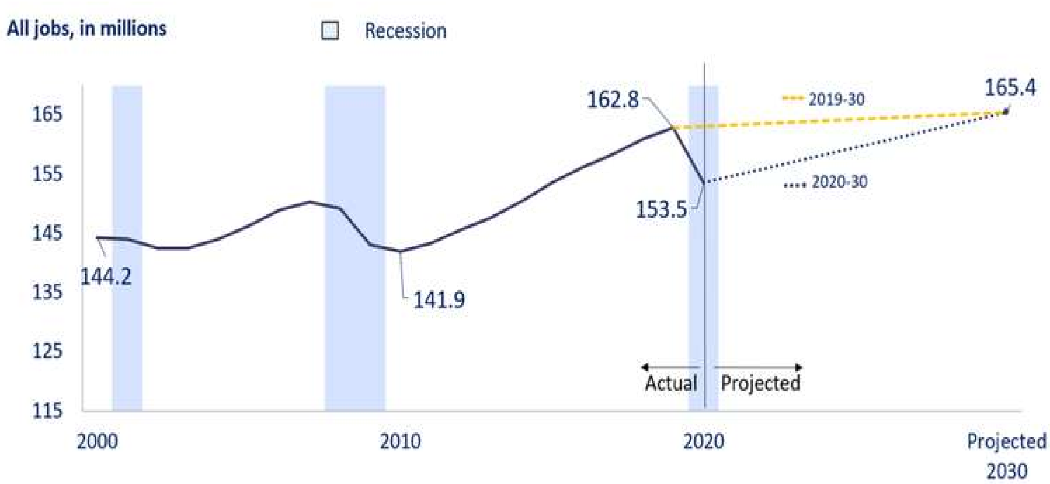

Figure 2. Construction Workforce Offset due to COVID 19

A Call for Innovation in Education

In a report by the Organization for Economic Cooperation and Development (OECD), it is noted that "the pressure to increase equity and improve educational outcomes for students is growing around the world" (Vieluf et al., 2012). Many in the USA seem to recognize that education at all levels critically needs renewal. Wildavsky et al. (2011) state that higher education has to change to include more innovation. An enhanced educational setting therefore produces the needed learning outcomes at all school levels. Jim Shelton, a former assistant deputy secretary of the Office of Innovation and Improvement in the US Department of Education, also posits that "Whether for reasons of economic growth, competitiveness, social justice, or return on tax-payer investment, there is little rational argument over the need for significant improvement in U.S. educational outcomes." Furthermore, it is undeniable that the US has only slightly improved on the majority of educational outcomes over the past few decades, especially when there has been a tremendous increase in investment over the same time period. In fact, rather than decreasing over time, the overall cost of producing each successful high school and college graduate has increased significantly, leading to what some refer to as an "inverted learning curve," (Shelton, 2011).

Today's education systems are required to be both effective and efficient, or in other words, to reach the goals set forth while making the best use of available resources" (Cornali, 2012, p. 255). This requires that the focus of educating future generations is geared towards a combination of learning theory and practice without ignoring the expectations of the learners, the communities, and societies being affected directly, and the impact on their way of life. As stated by Serdyukov (2017), "every technology application demands a solid theoretical foundation which will be hinged on a well-focused, logical research and sound training." Therefore, instructors engaging with students will need to be sensitive to the expectations of students to maximize their learning experiences (Mupinga et al., 2006).

Blokker, et al. (2019) emphasized that "career competencies are positively related to perceived employability and that the relationship between career competencies and career success mediates perceived employability." For educators seeking a unifying platform that embraces all stakeholders to connect through a common source of information sharing (i.e., a well-planned schedule to engage physically or by videoconferencing), one of the many possibilities is to take advantage of the surge in the use of virtual technology platforms for multilateral engagements. The innovative virtual platforms, the use of a virtual white board with annotation capacity to explain concepts, forming breakout rooms to create small collaborative group work, soliciting feedback from students through polls, and chatting to facilitate class discussions develops and enhances learners' engagement in the process.

Wyoming's Construction Education Systems

The construction sector plays a central role in the State of Wyoming's economic security. The lack of formal training causes construction skill attainment, income potential, and future career development to fall behind other states and impacts the profitability of local Wyoming construction companies. Construction careers have many opportunities that do not require a formal college degree but mandate the achievement of a postsecondary non-degree award before employment, a raise in pay, or an elevated position. Research shows that 15.6% of all construction employment in Wyoming requires a postsecondary non-degree award in the construction sector. Compared to 5.8% in the US and 2.3% in Colorado, Wyoming has the most significant percentage requirement at this level and category of education (Kofoed, 2021). The postsecondary non-degree award refers to a specialized program teaching focused content and skill knowledge to meet the criteria of this type of certification or license, along with completing high school education. After earning a postsecondary non-degree award, certified participants are qualified to work in their chosen field. The Wyoming Department of Education (2021) leverages the Carl D. Perkins Career and Technical Education Act of 2006 to support Wyoming CTE development. The express purpose of the Perkins Act is to provide tangible opportunities to follow, obtain, and elevate CTE positions by earning relevant credentials without requiring a college degree (*PCRN: Work-Based Learning*, 2020).

Description of the Overarching Educational Vision

The educational attainment level for the majority (53%) of construction employees is a high school diploma or less, with 29% obtaining some college, and 18% possessing a college degree or post-bachelor education. There needs to be an education program and provisions to bridge the gap for the majority of individuals working in the construction industry. The overarching vision, in support of creating a secondary and post-secondary construction education pathway, is to open the door for high school students to internship possibilities, and or full-time employment after graduating from high school. This vision is depicted in figure 3, where construction training at a high school level will allow a student to enter the construction workforce upon graduating from high school. A student can then re-enter the post-secondary education system at one of nine community colleges across the state in either a fulltime or part time capacity. A student can then transfer to a four-year institution to pursue a bachelor's degree. The educational platform will allow students to enter and re-enter the workforce platform at different entry points during their education journey. The overarching training model has been implemented at both high school and community colleges across the state of Wyoming.

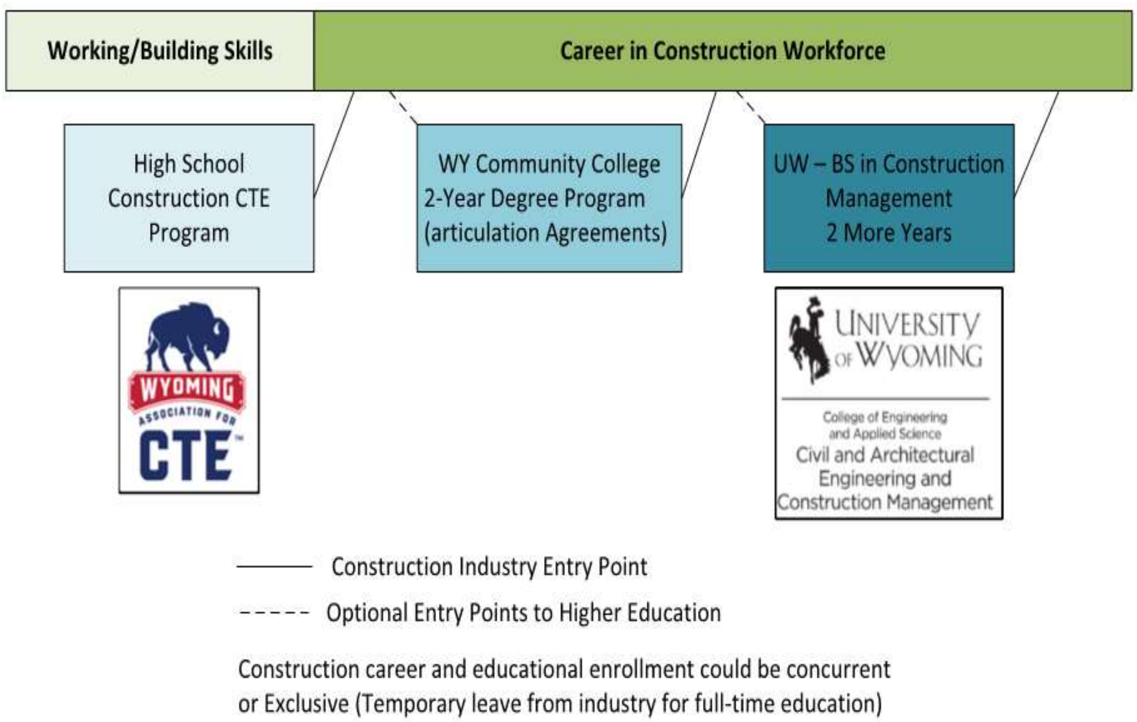

Figure 3. Construction Workforce Entry Platform

Construction Education Pathway Interventions

High School Content and Credentialing

The Construction Management program at the University of Wyoming has developed a high school training curriculum that allows high school Career and Technical Education (CTE) teachers to introduce students in their respective CTE programs to construction theories and concepts. Figure 4 represents the stackable structure of these training modules.

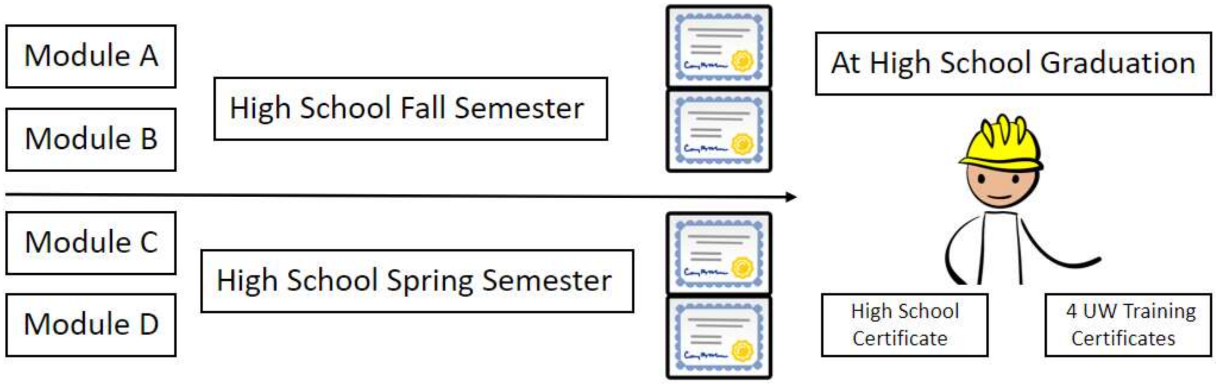

Figure 4. Stackable Construction Training Modules at High Schools

The modules are introduced to students during their high school senior year. Given the high school student employment prospects and the level of construction industry exposure, the modules focus on single family residential construction practice, with connected commercial construction content and examples interwoven throughout the curricula. The four modules comprise an introduction to construction plan reading (Module A), materials and methods (Module B), determining material quantities and costs (Module C) and project coordination and management (Module D). Modules A & B are administered during the fall and Modules C & D are administered during the spring of the high school student's senior year. The modules were designed to be administered on a bi-weekly basis as seen fit by the high school instructors of record. Each training module, both theoretical and practical, is made up of four sessions with each session comprising a one-hour university faculty directed pre-recorded lecture engagement, followed with group discussion and a guided classroom exercise.

All sessions have a one-hour homework assignment which is administered on the Canvas online platform, which is used by high schools across the state of Wyoming. These modules reflect partnerships developed with trade associations and business entities, who assisted in designing this training to provide all enrollees (high school students) with an estimated total of 32 contact hours, divided between the senior fall and spring semesters. Figure 5 illustrates the stackable module credential, which all students will be awarded after successfully completing each module. Upon the completion of all four modules, students receive a University of Wyoming construction certificate of accomplishment, which adds a certificate to the already pre-programmed high school certificate awarded by the high schools upon graduation. Every module is associated with an online exam, which students take under the supervision of the University of Wyoming to ensure the quality of the issued credential.

Figure 5. Stackable Module Credentials

An additional key component of this training is an internship, which provides real world experience, under the guidance of a mentor, sponsored by the company who provides the internship. Through this mentored experience, high school students who participate in this opportunity will have a head start in the employment realm. In fact, most students already work summer jobs, but an internship provides a clearer direction in the world of work when students graduate in May of each year. Sponsoring companies offer internships which best suit their needs. The partnership companies understand the value of such opportunities and have agreed to provide at least one internship that will lead to permanent employment for the protégé. The internship is the culmination of the training and provides individuals with the information needed in order to make decisions about life after graduation to either enter the workforce, attend a community college, or enroll in a four-year university degree program.

Data from the Wyoming Department of Workforce Services Research Office provides an indication of what an entry level in the construction workforce can earn. All categories of positions in the construction industry can benefit from the UW High School construction module training because the modules are structured around industry required skills. Figure 6 presents the wages of a selected few construction related positions.

Considering that the federal minimum wage for general employment is currently $7.25 per hour (*Wyoming Department of Labor & Employment*, 2022), this training and the internships provide opportunities for higher wages overall. In addition, all four construction training modules are connected to transferable high school CTE credits to a community college, in support of the following post-secondary intervention.

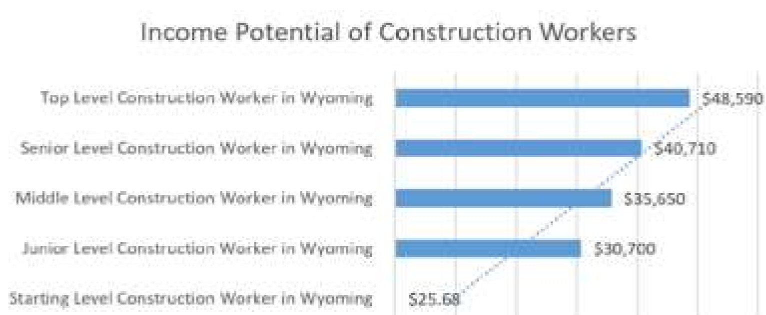

Figure 6. Construction and Extraction Occupations – Sep 2021 Wyoming Wage Survey

The Construction Management program at the University of Wyoming has further engaged with two institutions, Casper Community College, and Pathways Innovation Center, with the respective instructors of record and invited industry practitioners to co-teach a construction safety course. The focus of this intervention was to provide construction safety training to students at the respective institutions regardless of the different education level.

The inclusion of industry practitioners was to bring the lived experiences in the field of practice to the classroom and to bridge the gap between the theoretically based coursework and required industry skills. The enrolled students for each of the participating institutions comprised 27 University of Wyoming students, nine Casper Community College and 14 Pathways Innovation Center high school students. Zoom Meeting and the Meeting Owl Pro technology were the two videoconferencing technologies used during this teaching endeavor. With its improved functionality, the Meeting Owl Pro device, built to integrate easily with the Zoom Meeting platform, allows for multi-party virtual conferences by remotely detecting each speaker at any moment.

The instructors of record were each stationed with their students and connected with the other two campuses via the Zoom Meeting and Meeting Owl Pro platforms. The use of these live-intervention technologies worked well to cultivate educational synergy between the classrooms located at each of the institutions across the state.

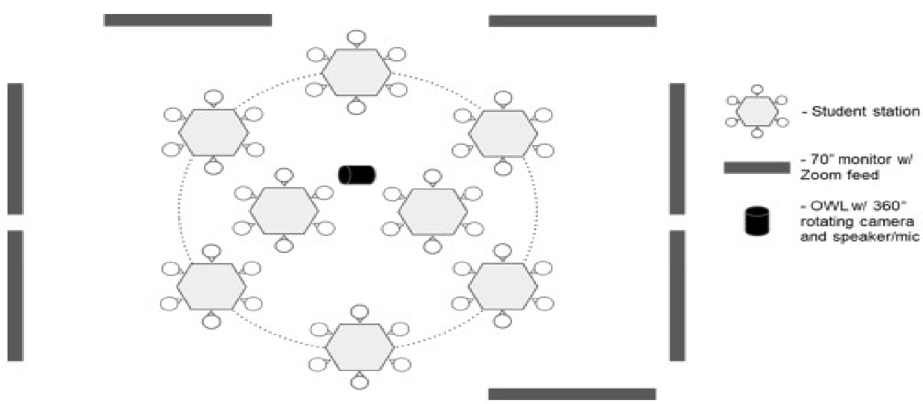

Figure 7. Schematic Classroom Setup in the Lecture Presentation Sessions

One challenge that was observed is the tendency for student to seek the same groups by sitting together during all lecture sessions. To avoid this concern and promote mixing of students from different educational levels, a ballot system was devised where students were located at a station base on random selection. The ballot process was repeated for all three learning stations to fully randomize student groups. Open-ended questions on the chapters covered by the delegated instructor of record and industry practitioner were discussed among students within each randomized group.

Conclusion and Considerations for Educators

This study provides construction educators with an exemplary framework that is currently being applied in Wyoming to address construction training and education from, and across, the High School, College and University systems. Given the anticipated 9% drop in high school graduates between 2026 and 2030, which is expected to have a detrimental impact on the construction workforce, it is critical that a rigorous training of professionals in the construction workforce is implemented. Many more triumphs could be attained by carefully adhering to a well-designed curriculum supported by industry professionals and sourcing for good technology like Zoom Meeting and Meeting Owl Pro that links all participants regardless of where they are located.

The application of these educational methods were utilized to underpin the current case study wherein connected secondary and post-secondary construction education initiatives were piloted to bridge the current, and anticipated, construction workforce skills shortage in the state of Wyoming. The results of these pilot programs proved to be the springboard needed to provide the kind of workforce training and skills enhancement being called for by the industry.

Wyoming is unique in that the state's educational system leads to a singular state university. While this, in many cases, is an advantage for Wyoming as it promotes a simpler articulation pathway, the small population that exists in the given land area of the state also poses challenges due to many communities having extremely limited resources, while also being geographically isolated from other educational institutions. Educators who are interested in connecting high-school, community college and university programs in their own state need to investigate and understand their state-specific educational landscape. Generally, the more colleges and universities in a state, the more articulation pathways, and educational standards there are to manage and maintain. One potential means to promote uniformity across the high school to community college to university transition is to use the American Council for Construction Education's (ACCE) student learning outcomes (SLOs) as standards for the development of connected curricula. The promotion of SLO-based curricula and student performance assessment-based testing provided a level of consistency and standardized metrics for knowledge gained as a construction-interested student progresses from high school to a community college and/or university while on the connected articulation pathway.

The development of this framework through industry and academic collaboration is an ongoing process. However, we believe it is well worth the time and energy it has taken to build it. The experiences of the learners and instructors speak volumes about the way to move forward in meeting the needs of both industry and future employees. As this program continues to be administered to a larger sample, further research will comprise the analysis of the data collected to empirically explore the impact of this program on student learning and desire in pursuing a career in the construction industry.

References

Associated Builders and Contractors (2022. August 5) ABC: Construction Employment Increases By 32,000 in July. Retrieved 10/18/22 from: https://www.abc.org/News-Media/News-Releases/entryid/19539/abc-construction-employment-increases-by-32000-in-july

Associated General Contractors. (2022, August 31) Construction Workforce Shortages Risk Undermining Infrastructure Projects as Most Contractors Struggle To Fill Open Positions. Retrieved October 12, 2022, from: https://www.agc.org/news/2022/08/31/construction-workforce-shortages-risk-undermining-infrastructure-projects-most-contractors-struggle

Blokker, R., Akkermans, J., Tims, M., Jansen, P., (2019) Building a sustainable start: The role of career competencies, career success, and career shocks in young professionals' employability. *Journal of Vocational Behaviour.* Volume 112, Page 172-184.

Bransberger, P. (2017). *Wiche Insights*. https://www.wiche.edu/wp-content/uploads/2018/10/ReportandDataTablesFINALrev10-17.pdf. Retrieved October 26, 2022, from https://www.wiche.edu/wp-content/uploads/2018/10/ReportandDataTablesFINALrev10-17.pdf

Wyoming Department of Labor and Employment (2022). Minimum Wage. Retrieved 10/25/2022 from https://cdle.colorado.gov/wage-and-hour-law/minimum-wage#:~:text=Federal%20minimum%20wage%20is%20currently,law%20beginning%20January%201%2C%202022.

Cornali, F. (2012). Effectiveness and efficiency of educational measures: Evaluation practices, indicators and rhetoric. *Sociology Mind*, *02*(03), 255–260. https://doi.org/10.4236/sm.2012.23034

Kofoed, A., (2021). Does Wyoming Reward a Postsecondary Education? 2021 Wyoming Workforce Annual Report, 55-54. https://www.dol.gov/sites/dolgov/files/eta/Performance/pdfs/annual_economic_reports/2021

Moore, J. L., Dickson-Deane, C., & Galyen, K. (2011). e-Learning, online learning, and distance learning environments: Are they the same? *The Internet and Higher Education, 14*(2), 129-135. https://doi.org/10.1016/j.iheduc.2010.10.001

Mupinga, D. M., Nora, R. T., & Yaw, D. C. (2006). The learning styles, expectations, and needs of online students. *College Teaching*, *54*(1), 185–189. https://doi.org/10.3200/ctch.54.1.185-189

Perkins Collaborative Resource Network. (2020) *Work Base Learning* https://cte.ed.gov/initiatives/work-based-learning

Serdyukov, P. (2017). Innovation in education: What works, what doesn't, and what to do about it? Journal of *Research in Innovative Teaching & Learning*, *10*(1), 4–33. https://doi.org/10.1108/jrit-10-2016-0007

Shelton, J. (2011, September 28). Education innovation: What it is and why we need more of it (opinion*)*. *Education Week*. https://www.edweek.org/education/opinion-education-innovation-what-it-is-and-why-we-need-more-of-it/2011/09

United States Bureau of Labor Statistics. (2021, October). Projections Overview and Highlights, 2020–30: Monthly Labor Review." Retrieved on 10/18/2022 https://www.bls.gov/opub/mlr/2021/article/projections-overview-and-highlights-2020-30.htm.

United States Bureau of Labor Statistics. (2022, September). Employment projections -- 2020-2030. Retrieved 10/18/2022 from: https://www.bls.gov/news.release/pdf/ecopro.pdf

Vieluf, S., Kaplan, D., Klieme, E., Bayer, S. (2012). Teaching Practices and Pedagogical Innovations: Evidence from Talis. OECD Publishing. https://www.oecd.org/education/school/TalisCeri%202012%20(tppi)--Ebook.pdf

Wildavsky, B., Kelly, A., & Carey, K. (2011). Reinventing higher education: The promise of Innovation. *The Review of Higher Education, 37*(1), 137–140. https://doi.org/10.1353/rhe.2013.0058

Wyoming Department on Education. (2020). 2021 Perkins V Plan. Retrieved 10/25/2022 from: https://edu.wyoming.gov/wp-content/uploads/2020/08/2020-2021-ADA-Verified-Perkins-Plan-With-Attachments-1.pdf

Mathematics and Science Subjects in Construction Management Baccalaureate Programs

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This study analyzes credit-hours of mathematics and science subjects in the American Council for Construction Education (ACCE) accredited bachelor's degree programs in Construction Management (CM). As per the current ACCE standards, a graduate of a CM program is required to complete 3 and 6 Semester Hours (SHs) in Mathematics and Science, respectively. An analysis of the credit-hours in the 75 accredited programs shows that more than 90 percent of the programs require a student to complete more hours in these subject than the required 9 SHs. The analysis also shows that 72 percent of the programs require 6 SHs or more in Mathematics and 79 percent of the programs require 8 SHs or more in Science. A strong presence of mathematics and science subjects in the CM programs indicates that the programs are striving to equip the graduates with skills in data analysis, model building, and research and innovation. Moreover, these subjects equip the graduates for a continuous academic inquiry and prepare them to understand and appreciate the natural world. The results indicate that the CM programs make a strong case for science, technology, engineering, and math designation.

Key Words: ACCE accreditation, Mathematics, Science, STEM, Student learning outcomes

Introduction

The number of workers entering the construction industry in the coming years is projected to grow and so is the demand for the construction management (CM) graduates. Hovnanian, Luby, and Shannon (2022) project that about 300,000 to 600,000 new workers will be entering in the non-residential construction sector alone each year. Furthermore, Thomasian (2011) predicted that science, technology, engineering, and math (STEM) jobs are expected to grow twice as fast as non-STEM jobs and more than 90 percent of these jobs "will require postsecondary study, with 68 percent requiring a bachelors' degree or more" (p. 12). This trend is reflected in the growth over the years of the CM programs offering a baccalaureate degree. The number of baccalaureate degree programs accredited by the American Council for Construction Education (ACCE) increased from 60 in 2006 to 73 by the 2015-16 school year (Smith-Barrow, 2017). As of 2022, the number of CM degree programs has further increased to 75 (American Council for Construction Education [ACCE], 2022a) and there are currently five bachelor's degree Candidate programs waiting for full accreditation and three Applicant programs under consideration for a Candidate program (ACCE, 2022b).

The CM programs have not only grown in numbers, they also have stood the test of time to establish themselves as independent programs with unique identity. Hauck (1998) and Rounds (1992) argue that, although the construction management programs in the universities started as a branch within the Engineering and Architecture departments, the programs have gained acceptance as a distinct academic area. Along with the growth in the numbers and recognition as a distinct academic area, the programs are being "developed in nontraditional academic departments, such as business, construction technology, industrial science, and industrial technology" (McDaniel, 2005, p.5). These programs, as Dietz and Litle (1976) and McDaniel (2005) observe, have shifted their emphasis from basic science, mathematics, and design to focus more on construction technology and management. The trend of less emphasis on mathematics and science is reflected in the ACCE accreditation requirements too. The ACCE standards currently require a minimum of 3 and 6 Semester Hours (SHs) in the core areas of mathematics and science, respectively (ACCE, 2022c). The requirements in the years before 2016 were a minimum of 3 SHs in mathematics and 8 SHs in science with a minimum of 15 SHs required for a combination of these two subject areas such as in ACCE (2012). Effective from 2016, the ACCE standards also moved from a suggested list of subjects in various categories to a list of 20 Student Learning Outcomes (SLOs) that a student must achieve to graduate (Batie, 2018).

Although none of the SLOs is related to mathematics and science, the commentary on the ACCE standards provides rationales for these subjects. The commentary states that "construction is in part a technical process that can be best controlled by applying the principles of mathematics and statistics. An understanding of the behavior of the materials, equipment, and methods used in construction requires knowledge of the physical and environmental sciences" (ACCE, 2021, p. 13). Additionally, it can be argued, as Glaze (2018) suggests, that science literacy equips the graduates with an ability to "solve problems, make evidence-based decisions, and evaluate information in a manner that is logical" (p. 1). As Mills, Auchey and Beliveau (1996) and Hauck (1998) also argue, the cornerstone of a strong CM curriculum is balancing between practical experience, technology management and academic inquiry. Literacy in mathematics and science prepares the graduates with skills in academic inquiry and ability in evidence-based decision making. Although it can be argued that mathematics and science are essential building blocks of construction management education, it is difficult, if not impossible, to argue on the minimum required number and nature of such courses. Against this background, this study analyzes the extent to which the ACCE accredited bachelor's degree programs require mathematics and science subjects in their respective programs. The main research questions of this study are:

1. What is the variation in credit hours of mathematics and science subjects in the programs?
2. What is the extent of the mathematics subjects offered in the programs?
3. What is the extent of the science subjects offered in the programs?

Along with the above research questions, an argument based on the results of the analysis is made for considering the CM degree programs under a STEM classification.

Data consideration and assumptions

The programs considered in this study are from a current list of the ACCE accredited bachelor's degree programs as of August 08, 2022 available from the ACCE website (ACCE, 2022a). Information about the programs was collected from the webpages of the respective programs during August and September of 2022. The subjects and the corresponding credit-hours were recorded from the suggested roadmap of the respective programs as far as available. In the case where the roadmap was not available, the required subjects were recorded from the degree requirement descriptions and the subject list available on the program webpage. Following assumptions are made in the analysis.

- The minimum required credit-hour as suggested in the course map is considered in the analysis. For example, if a student can choose between a 4-hr and a 5-hr course, 4-hr is used in the analysis.
- A course title is used to identify the nature of the course. For example, if a course title includes Precalculus, it is assumed that the course does not cover Calculus.
- In case a program offers an option to choose between Physics or Chemistry and other Science courses, other Science courses are accounted for in the analysis.

Math and Science requirements

Out of a minimum of 120 SHs required for a bachelor's degree program for the accreditation purpose, the ACCE standards prescribe only 83 SHs in General Education (GE), Business and Management and Construction categories (ACCE, 2022c). The standards state that a Degree Program can use the remaining 37 SHs in any way it wants to meet “ACCE SLOs, Degree Program-specific focus or specialization, and other institutional requirements” (ACCE, 2022c, p. 11). Moreover, as academic programs are designed to serve their respective constituencies, the programs are expected to have a certain degree of diversity in the admission requirements, subjects covered, depth and breadth of the coverage and graduation requirements. The programs accredited by ACCE, as such, also are expected to have such variations. ACCE also encourages the programs to “strive to provide offerings that exceed the ACCE standards and criteria for accreditation (ACCE, 2021, p. 12). In addition to the required credit-hours, the standards also prescribe 20 student learning outcomes (SLOs) which a bachelor's degree program needs to meet for the ACCE accreditation.

Out of the 83 SHs, the ACCE standards require a minimum of 15 SHs in the GE category and the subjects must be taught outside the degree program (ACCE, 2022c). Areas in GE include communications, mathematics and physical or environmental science with a minimum required hour for each sub-category as 6, 3 and 6 SHs, respectively. Therefore, a student must complete a minimum of 9 SHs or 7.5 percent of the total hours in mathematics and science to graduate. Despite of the hours allocated, there is no learning outcome that can be associated directly with the subjects in the mathematics and science sub-category. Although not stated explicitly in the SLOs, the expectations from mathematics and science subjects are laid out in the commentary sections of the standards. The commentary documents explain that the curriculum should be responsive to reflect the application of evolving knowledge in the behavioral and quantitative sciences and every student possesses a well-developed concept of mathematics as technical processes need application of the principles of mathematics and statistics (ACCE, 2021).

An analysis of the required credit-hours in mathematics and science in the ACCE accredited CM programs show that majority of the programs require their students to complete 10 percent or more of the total required credit-hours in mathematics and science subjects (Figure 1). Only three out of the 75 accredited programs have eight percent or less of the total credit-hours dedicated to these subjects. The credit-hours used in Figure 1 exclude required hours for Algebra and Trigonometry but include hours for Statistics. The ACCE standards state that Algebra and Trigonometry cannot be considered for the required 3 credit-hour in mathematics but hours in Statistics can be considered (ACCE, 2021 and ACCE, 2022c). A detailed discussion on the nature and composition of science and mathematics subjects in the CM programs is done in the following sections.

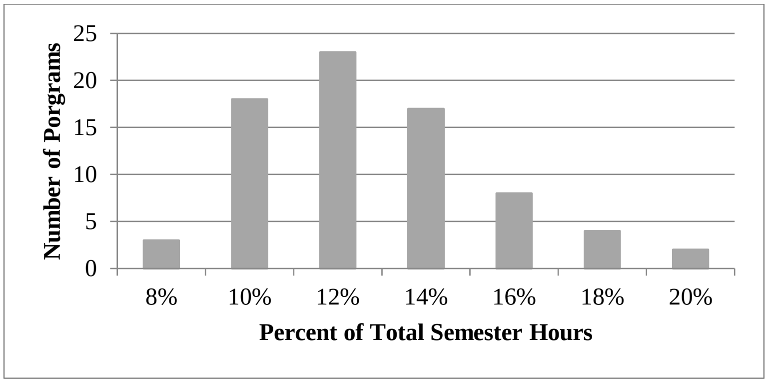

Figure 1. Mathematics and Science credit hours as a percentage of total credit hours in the ACCE accredited CM bachelor's degree programs

Math courses in Construction Management programs

The ACCE standards state that the degree programs "shall not use a college algebra course or trigonometry course for this requirement" (ACCE, 2022c, p. 10) which implies that acceptable level of mathematics is Precalculus or above it or Statistics. The required credit-hours in mathematics in the CM programs are shown in Figure 2. In the figure, hours in Statistics are included but those in Algebra and Trigonometry are excluded in line with the ACCE criteria. For a comparison purpose, Quarter-hours (QHs) are converted to SHs by a factor of 3/4 as ACCE criteria require a minimum of 3 SHs or 4 QHs in mathematics. More than 70 percent of the programs require a student to complete two times or more than the minimum required 3 SHs to graduate from the program. Out of the 75 programs, only 13 programs require the minimum prescribed hours.

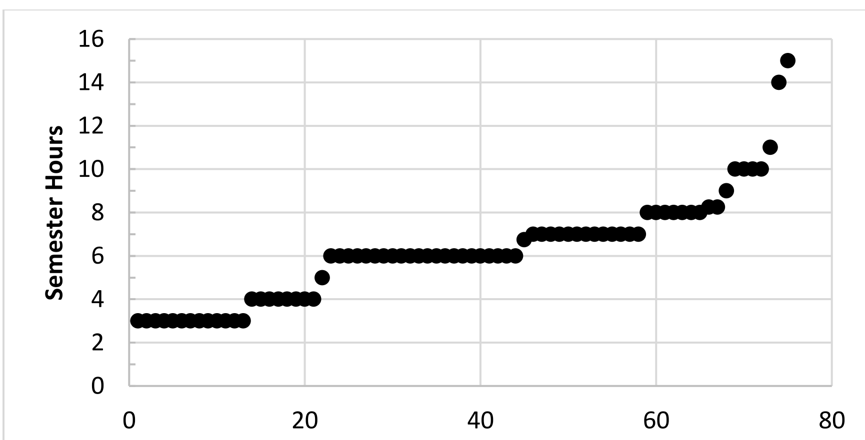

Figure 2. SHs in mathematics in the CM programs. Hours in Algebra and Trigonometry are excluded but the hours in Statistics are included.

Although Trigonometry and Algebra cannot be counted towards the ACCE requirements, many programs require their students to complete these subjects. One of the reasons for this may be that the programs have different admission requirements and students are required to complete these subjects to build the foundation knowledge for higher level mathematics and construction science courses.

Figure 3 shows information on number of programs requiring Trigonometry and Algebra courses. As can be seen in the figure, 49 programs, or 75 percent, do not require a graduate to complete any Algebra and Trigonometry course. Out of the 26 programs that require credit-hours in these subjects, 12 programs require 3 or less SHs and only seven programs require 6 or more SHs.

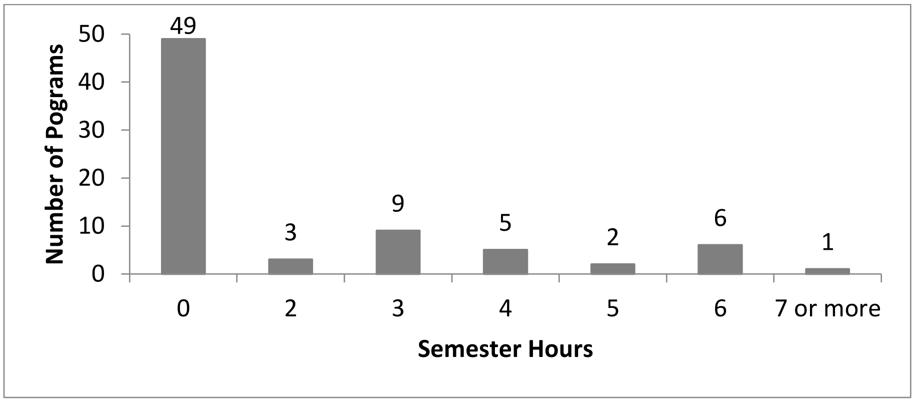

Figure 3. Semester Hours in Algebra and Trigonometry in the CM programs

Figure 4 shows status of Pre-calculus, Calculus and Statistics, which are the subjects that can be used against the ACCE requirements, in the CM programs. Statistics is considered more applied mathematics than a pure mathematics subject. For example, Johnson and Kuennen (2006, p. 1) consider that "while advanced statistics is very much a mathematical discipline, introductory statistics is generally considered not to be a mathematics course". However, the ACCE standards consider that Statistics can be used to meet the ACCE requirements in mathematics. Out of the 75 programs, three programs (four percent) use only Precalculus to meet the ACCE criteria. Among the programs, 70 percent have at least one Calculus course and 75 percent have at least one Statistics. Forty nine percent programs require at least one course of both Calculus and Statistics.

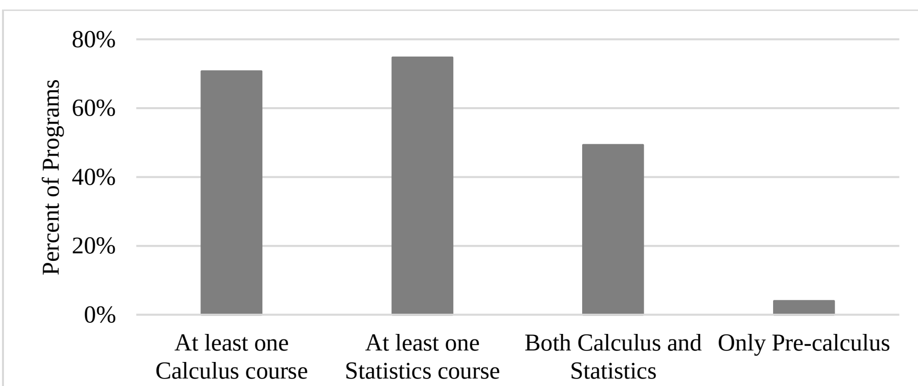

Figure 4. Precalculus, Calculus and Statistics in the CM programs

Science courses in Construction Management programs

The ACCE standards include physical and environmental science in the category of science subjects and require that the subjects shall be analytically based and not descriptive (ACCE, 2022c). Furthermore, the science subjects are expected to be taught outside of the degree program. The ACCE standards further recommend that the courses in the science category "should include the use of analytical skills, such as mathematics and scientific reasoning—often associated with lab skills" (ACCE, 2021, p. 15). Figure 5 shows the credit hours in science subjects in the 75 ACCE accredited degree programs. Six programs require a student to complete only the minimum required credit hours required by ACCE. As can be seen in Figure 5, many of the programs require a student to complete 8 or more SHs which is 1.3 times higher than the minimum required credit-hour in science.

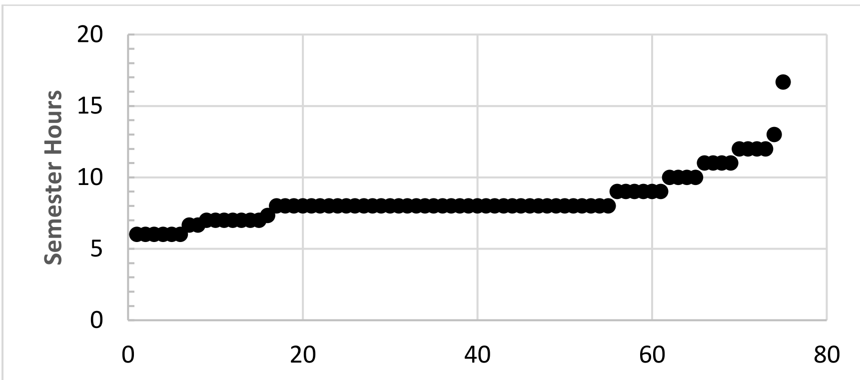

Figure 5. SHs in Science subjects in the CM programs

Figure 6 shows the percentage of programs requiring Physics and Chemistry subjects a student must complete to graduate from the degree program. Ninety-five percent of the programs require that the students complete at least one Physics course but only 15 percent of the programs require a course in Chemistry. As seen in the figure, 32 percent of the programs quire to complete 6 SHs or more of Physics which is sufficient to meet the accreditation requirement in science. Forty four percent of the programs require students to take both Physics and Chemistry such that the combined hours are sufficient to meet the requirements in science.

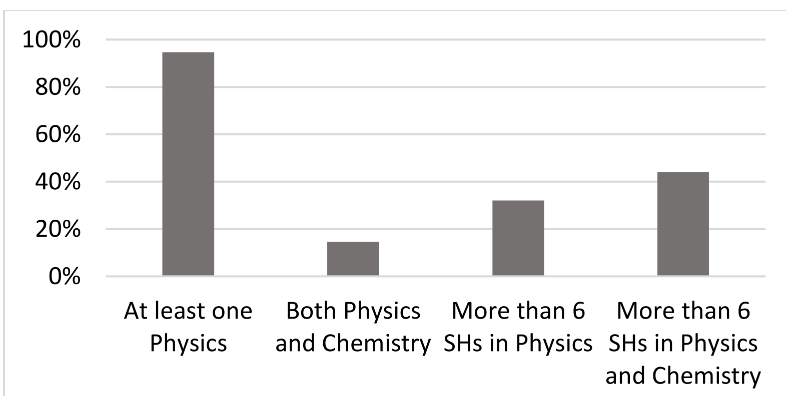

Figure 6. Physics and Chemistry courses in the CM programs

Discussion on ACCE learning outcomes and STEM classification

Mathematics and science learning outcome

The hallmark of the ACCE standards has been layering of construction courses, comprising of construction technology and construction management, with foundational courses on mathematics and science. It can be argued that mathematics and science subjects are required in construction management for three reasons. First, they bridge the gap between what the students have learned in high school and what is required for successfully completing the construction courses. Second, the courses in mathematics and science prepare the graduates to formulate a problem, build a model, develop and conduct experimentation, analyze and interpret the data and make arguments based on evidence. Third, and most importantly, the courses prepare a graduate for continuous academic inquiry and to understand and appreciate the diversity and unity of the natural world. Overall, the epistemic practices and the learning and knowledge "produced through such practices as building models, argument from evidence, and communicating findings" (Moon & Singer, 2012, para. 6) in mathematics and science prepare the graduates for application of the construction management knowledge in professional practice and engage in a life-long pursuit of academic inquiry.

It appears that the intention of the ACCE standards in prescribing the requirements in mathematics and science is related with all the three aspects explained above. Although none of the current 20 SLOs in the ACCE standards is related to the mathematics and science subject areas, the intention is stated in the commentary. The commentary on the ACCE standards states that "construction is in part a technical process that can be best controlled by applying the principles of mathematics and statistics. An understanding of the behavior of the materials, equipment, and methods used in construction requires knowledge of the physical and environmental sciences" (ACCE, 2021, p. 13). Given the intention of the standards and the presence of mathematics and science course in the CM programs, it seems logical that the ACCE standards include at least one comprehensive learning outcome to capture the essence of what graduates are expected to accomplish from completing the mathematics and science courses.

STEM classification of CM program

The definition of what exactly is STEM and which majors fall under the STEM field are still to be settled. Despite the proliferation of STEM related policies and entities, the exact understanding of STEM branding itself is still elusive (Moon & Singer, 2012). While the National Science Foundation uses a broader definition of STEM to include psychology and the social sciences, Department of Homeland Security (DHS) uses a narrower definition which excludes social sciences and focuses on areas like mathematics, chemistry, physics, and engineering (Gonzalez & Kuenzi, 2012).

Although the definition of STEM fields is still to be settled, CM programs with a mix of science, math, technology, and management subjects are considered, by default, as the STEM subjects, for example, in Jones, Rusch and Waggenspack (2014) and John and Chen (2017). The DHS's latest STEM designated degree program list, however, does not include Construction Management in the STEM field (Department of Homeland Security [DHS], 2022). The DHS program list is used for the purpose of 24-month STEM optional practical training extension. Therefore, a program with a STEM designation can attract more international students as they will be eligible to apply for an extension of 24 months of work visa. STEM classification can be attractive to domestic students too as such a classification carries more weight than ever (Kullman, 2019) and students can have a competitive edge in the job market. “Construction Management” falls in the category of Business, Management, Marketing, and Related Support Services under the current Classification of Instructional Programs (CIP) which is used by DHS to prepare the STEM list. As of 2022, DHS lists only “Management Science”, “Business Statistics”, “Actuarial Science”, and “Management Science and Quantitative Methods, Other” under the STEM field within this CIP category.

Although a STEM designation can boost the number of applicants and can be instrumental in solving the gap in skilled workers in the construction industry, there is more to a STEM designation than to increase the enrollment. As the construction industry needs to evolve, adapt to and be at the forefront of the technological innovations that are sweeping through the industry, the programs also need to prepare the graduates to lead the industry through these changes. A STEM designation can steer the programs to prepare the graduate to be at the forefront of technological innovation and to apply data analysis, risk management, modeling and research and innovation. Realizing the need for STEM classification, many business and management programs, including the CM programs, have recently moved from a non-STEM to a STEM classification. All three MBA programs of UC-Berkeley’s Haas School of Business were reclassified from “Business Administration and Management, General,” to “Management Science,” which falls under the STEM field (Ethier, 2019). Similarly, Arizona State University’s CM program was moved from a “Business Management” program to a “Construction Engineering Technology/Technician” classification which is a STEM field (Kullman, 2019). As the ACCE criteria already require several foundational courses in mathematics and science and courses in construction science and technology, the CM programs meet the requirements for a STEM classification on their own instead of them requiring to change the departmental affiliation. In addition to the requirements in mathematics and science, the ACCE standards require a graduate to be able to create cost and schedule estimates, analyze methods, materials and equipment, apply surveying techniques, understand accounting, cost control, risk management and structural behavior and apply digital technology for managing construction processes. Therefore, it can be argued that the CM programs have a genuine case for the STEM designation.

Conclusion

An analysis of the credit-hours of mathematics and science subjects in the ACCE accredited CM programs shows that the programs require a graduate to complete more hours in these subjects than required for the accreditation. More than 90 percent of the CM programs require graduates to complete more hours in mathematics and science subjects than required by the ACCE accreditation. As the current list of SLOs required for accreditation does not have an outcome related to these subjects, it is argued that the standards should have at least one learning outcome related to mathematics and science subjects. The ACCE accreditation standards require that the CM graduates are not only equipped with managerial skills, but they are also prepared for data analysis, innovation and research, and scientific reasoning, Therefore, CM programs make a convincing case for STEM recognition in the CIP classification and the DHS’s list.

References

American Council for Construction Education. (2012). *Document 103: Standards and Criteria for Accreditation of Postsecondary Construction Education Degree Programs – Rev 3/12; Effective 7/12*. Received in an email communication from the ACCE on Oct 17, 2022.

American Council for Construction Education. (2021). *Document 104: Standards and Criteria for Accreditation with Commentary*. Retrieved from: https://www.acce-hq.org/file-share/b05b9c92-2275-42f2-83d3-eced5fbb783b

American Council for Construction Education. (2022a). *ACCE Bachelors Programs 2022.08.08.* Retrieved from https://www.acce-hq.org/accredited-degree-programs

American Council for Construction Education. (2022b). *ACCE Candidate and Applicant Programs 2022.08.08*. Retrieved from https://www.acce-hq.org/accredited-degree-programs

American Council for Construction Education. (2022c). Document 103: Standards and Criteria for Accreditation of Construction Education Programs. Retrieved from: https://www.acce-hq.org/file-share

Batie, D. L. (2018, June). Outcomes assessment in an ACCE construction management program. In *2018 ASEE Annual Conference & Exposition*.

Department of Homeland Security. (2022). *DHS STEM Designated Degree Program List Last Updated: Jan. 21, 2022.* Retrieved from https://www.ice.gov/doclib/sevis/pdf/stemList2022.pdf

Dietz, A. G., & Litle, W. A. (1976). Education for construction. *Journal of the Construction Division*, 102(2), 347-364.

Ethier, M. (2019, November 18). UC-Berkeley Haas' MBA Programs Are All STEM-Designated Now. *Poets and Quants.* Nov 18, 2019. Retrieved from https://poetsandquants.com/2019/11/18/uc-berkeley-haas-mba-programs-are-all-stem-designated-now/

Glaze, A. L. (2018). Teaching and learning science in the 21st century: Challenging critical assumptions in post-secondary science. *Education Sciences*, *8*(1), 12.

Gonzalez, H. B., & Kuenzi, J. J. (2012, August). *Science, technology, engineering, and mathematics (STEM) education: A primer.* Washington, DC: Congressional Research Service, Library of Congress.

Hauck, A. J. (1998). Construction management curriculum reform and integration with a broader discipline: A case study. *Journal of Construction Education*, 3(2), 118-130.

Hovnanian, G., Luby, R., & Peloquin, S. (2022, April 6). *Bridging the labor mismatch in US construction*. McKinsey & Company. Retrieved September 22, 2022, from https://www.mckinsey.com/capabilities/operations/our-insights/bridging-the-labor-mismatch-in-us-construction

Johnson, M., & Kuennen, E. (2006). Basic math skills and performance in an introductory statistics course. *Journal of statistics education*, 14(2).

John, D. D., & Chen, Y. (2017, June). STEM Education Redefined. In *2017 ASEE Annual Conference & Exposition*.

Jones, S. C., Rusch, K. A., & Waggenspack, W. N. (2014, June). S-STEM: ENG2 Scholars for Success 2007-2013. In *2014 ASEE Annual Conference & Exposition* (pp. 24-1063).

Kullman, J. (2019, February 20*). STEM designation is step up for construction management program.* Retrieved from https://fullcircle.asu.edu/fulton-schools/stem-designation-step-up-construction-management-program/

McDaniel, D. (2005). Developing an integrated curriculum model for construction management education. *Online Journal for Workforce Education and Development*, 1(3), 2.

Mills, T. H., Auchey, F. L., & Beliveau, Y. J. (1996). The development of a vertically and horizontally integrated undergraduate building construction curriculum for the twenty first century. *Journal of Construction Education*, 1(1), 34-44.

Moon, J., & Singer, S. R. (January, 2012). Bringing STEM into focus. *Education Week*, 31(19), 32.

Rounds, J. (1992). Construction education: On the brink. *In ASC 28th Annual Conf*, pp. 145-150.

Smith-Barrow, Delece. (2017, August 10). "Report: More College Students Choosing to Major in Construction than Ever Before". *U.S. News & World Report*. Retrieved from https://www.constructionequipmentguide.com/report-more-college-studentschoosing-to-major-in-construction-than-ever-before/35785

Thomasian, J. (2011). *Building a science, technology, engineering, and math education agenda: an update of state actions*. NGA Center for Best Practices.

Value added to small residential homes due to energy efficiency measures

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Energy efficiency has become one of the preferred features for homebuyers. Today, energy-efficient houses are valued more on the housing market since there is a significant emphasis on environmental consciousness. Energy-efficient homes are rated as superior homes due to their role in reducing utility bills. Fannie Mae, Freddie Mac, and Federal Housing Administration (FHA) have developed policies and guidelines to help appraisers assess the energy-efficient features of a home. However, the appraisers do not generally add value of energy-efficient measures due to difficulties in estimating the benefits. The home appraisers will welcome a tool that could help them estimate the benefits of an energy efficiency measure and will use it in their appraisals. The tool developed in this study will consider the most common home energy efficiency measures (EEMs) in four categories: space conditioning, hot water, enclosures, and lighting/appliances, and estimate the initial cost of adding them to a home as well as their annual energy savings. Spreadsheets are developed for a small size home in Gainesville, Florida that allow the home appraisers find the present worth of an added energy efficient measure based on the remaining life of the home, the energy inflation rate, and the discount rate.

Keywords: Home Appraisal, Energy Efficiency Measures, Energy Saving, Payback Period

Introduction

Home appraisal is normally considered an unbiased professional estimate of the fair market value of a home or property and is ordered by lenders during the mortgage loan process. The lender’s goal is to make sure that the amount of money requested by the borrower is proper (Fontinelle, 2019; Williamson, 2022). However, this procedure is often difficult, an error-prone attempt, and time consuming. Many lenders such as banking institutions want to achieve a precise appraisal of a building, home, or other commercial or residential properties (Williamson, 2022). Without an accurate appraisal, there is no guarantee for lenders to know if they are lending the fair amount for the property, and there is no way for borrowers to understand if they are paying a fair market value for the home (Homes, 2019). A home appraisal is a key part of the transaction whether using a mortgage, refinancing the existing mortgage, or selling the home to a person other than all-cash buyers. The owner, buyer, or seller needs to know how the appraisal process works and how appraisers assess a home’s value. Indeed, the appraiser should normally be hired by the lender, and the appraisal fee which could be several hundred dollars is generally paid by the borrower (Fontinelle, 2019).

Energy-efficient homes should sell for higher prices due to the added value of energy efficiency features and the lower utility bills for homeowners. Fannie Mae, Freddie Mac and FHA guidelines require appraisers to consider the energy efficient features of the home and make an adjustment in the appraised value. However, energy efficiency can be overlooked in the appraisal process due to appraiser qualifications and a lack of access to quality data. Doyle and Bharagava (2012) reported numerous challenges to develop adequate valuation for energy efficiency, such as the lack of valuation sources for energy efficiency improvements and lack of collaboration between stakeholders. They concluded that proper valuation would encourage investment in energy efficiency, create jobs, and increase energy independence benefits.

On July 28, 2022 a legislation named "Getting Renewable and Energy Efficient Neighborhoods (GREEN) Appraisals Act" was introduced in the U.S. House and Senate to encourage energy efficient and renewable features to be considered as part of the residential homebuying and appraisal process. This legislation is aimed at ensuring home appraisals accurately reflect the value of renewable and energy efficient features of a property (GovTrack, 2022).

Appraising energy-efficient homes when there are so few comparable and the homes are equipped with heat pump water heaters, low E windows, LED lights, and EnergyStar appliances is a huge task.
The goal of this paper is to provide appraisers with a tool that could help them estimate the benefits of an energy efficiency measure and use it in their appraisals. The tool developed in this study will allow the home appraisers to find the present worth of an added energy efficient measure based on the remaining life of the home.

Background

Home Appraisal

An appraisal should protect the interests of both the borrower and the lender. The appraisal can cover the current condition of the property, recent sales information for similar properties, the location of the property, i.e., insight as to how the neighborhood affects the property's value (Williamson, 2022). The most important tool an appraiser uses during appraisal is comparable sales. This mentions the prices of homes of a similar size, age, and construction to the property being appraised that have recently been sold in the same neighborhood (Thompson, 2018).

Appraisals are usually performed by specially trained professionals who are certified to assess the value of a home objectively and impartially. An appraiser must be a specialist on the housing market and be familiar with the local market circumstances. While no appraiser is flawless, his or her opinion of the value of the home is often informed by training, numerous tests, years of experience and required continuing education. Appraisers are also required to prove every finding in their reports that could have impact on home's value (Appraisal Institute, 2019; Fontinelle, 2019; Williamson, 2022). It is understood that the appraiser does not work for the interests of anyone, because their only job is to evaluate the property and give a reasonable estimate of its worth (Homes, 2019).

While price, location, and design are a home buyer's major considerations (Appraisal Institute, 2019), the appraisal is generally based on the property's physical characteristics such as the number of bedrooms and bathrooms, square footage, location, age, lot size, and view (Hewes & Peeks, 2013; Williamson, 2022). The appraiser checks the inside factors such as functional layout and how well the space is designed, the size of major rooms such as the kitchen in comparison to the magnitude of the other rooms, the electrical, mechanical, and plumbing systems, safety and health matters like fire escapes and handrails, and the quality and number of home appliances.

Energy Efficiency

Energy Efficient Homes

A notable amount of energy consumption comes from the residential sector, which was around 17 percent of total energy usage in the United States in 2020 (U.S. Energy Information Administration, 2021). Building activities consume more than 30 percent of worldwide energy production and emit over 30 percent of the process-related global greenhouse gases (Fenner et al., 2020). Therefore, energy efficiency is one of the most advisable home features which buyers are willing to pay more for (Appraisal Institute, 2019; EnergySage, 2018). Electric heater, air conditioner, water heater, and electronics account for the main parts of a home's energy bill, therefore it is necessary to decrease the energy usage of these parts. Figure 1 shows the share of electric consumption for a typical house in U.S.

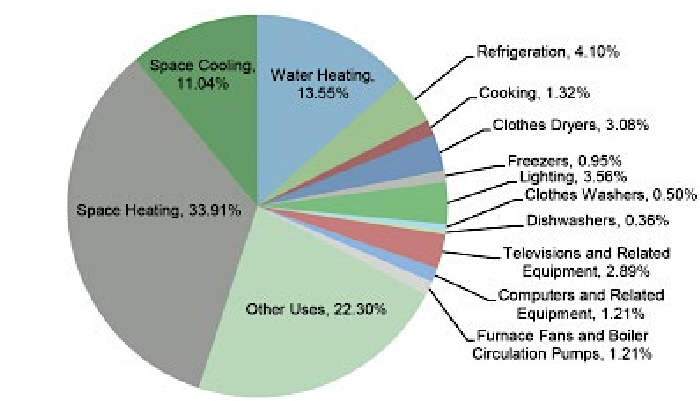

Figure 1. U.S. Residential Energy Consumption by End Use, 2019 (Source: Energy Information Administration, 2020)

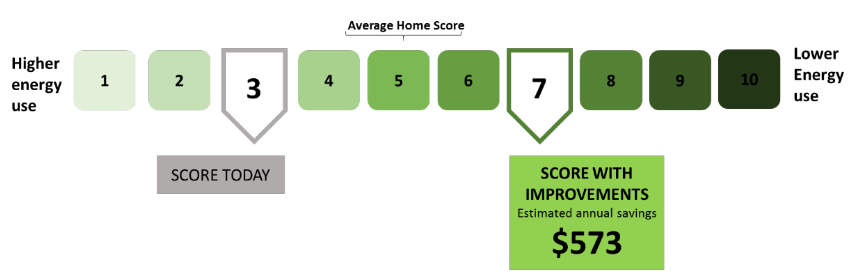

Figure 2. The relation between home energy score and energy consumption (U.S. Department of Energy, 2016)

Energy Efficiency Measures (EEMs)

The site conditions, occupant behavior, and climate are some of the factors that affect the energy consumption of homes. In addition, there are some measures that reduce energy use of homes, which are called Energy Efficiency Measures (EEMs). The four major categories for EEMs are space conditioning, hot water, enclosures, and lighting/appliances (Burge, 2016; Talbot, 2012).

The U.S. Department of Energy (DOE) established a national rating system to improve energy efficiency of homes. A score of one to ten is assigned to a home, where the score of ten represents the most efficient home. The score is mainly based on the building envelope, cooling, heating, and hot water. Figure 2 demonstrates that higher scores cause lower energy consumption (U.S. DOE, 2016).

The other approach to reduce energy consumption is to design homes based on national model energy codes such as those that are developed by ASHRAE and the International Codes Council (Athalye et al., 2016; Cohan, 2016). Homes built based on the 2012 or 2015 International Energy Conservation Code (IECC) are around 15 percent more energy efficient and have lower monthly utility bills than the previous codes. One of other strategies to improve energy efficiency of homes is the “ENERGY STAR” certification, which is established by the Environmental Protection Agency (EPA) in 1992. ENERGY STAR certified homes are at least 10% more energy efficient than non-certified homes (energystar.gov).

The other energy efficiency rating system is the Home Energy Rating System (HERS) Index by the Residential Energy Services Network (RESNET). A certified Home Energy Rater assesses the energy efficiency of a home by calculating its energy use for several end-uses such as heating, cooling, and water heating and assigns a relative performance score. The lower the number, the more energy efficient the home. A home with a HERS Index Score of 130 is 30% less energy efficient than a standard new home. The U.S. DOE has determined that a typical resale home scores 130 on the HERS Index while a standard new home is awarded a rating of 100.

Policies and guidelines to include EEMs in home appraisal

The Federal National Mortgage Association, commonly known as Fannie Mae, is a U. S. government-sponsored enterprise and, since 1968, a publicly traded company. Whether to buy or refinance a home, Fannie Mae presents HomeStyle® Energy mortgage loan to improve energy and water efficiency and decrease utility costs. This type of loan may be the most affordable financing way for energy-efficient purposes (Fannie Mae website).

The Federal Housing Administration is a U. S. government agency created in part by the National Housing Act of 1934. The FHA sets standards for construction and underwriting and insures loans made by banks and other private lenders for home building. In 1992, the Department of Housing and Urban Development (HUD) launched the Energy Efficient Mortgage as a pilot program in five states and developed it into a national program in 1995. FHA's Energy Efficient Mortgage program (EEM) encourages homeowners to reduce utility costs by financing energy-efficient upgrades with their FHA-insured mortgage. Cost-effective energy upgrades can decrease utility bills and gain more income available for the loan payment (FHA website).

The Federal Home Loan Mortgage Corporation, known as Freddie Mac, is a public government-sponsored enterprise. Freddie Mac offers the GreenCHOICE Mortgage® loan to assist homeowners in keeping their home affordable over time by reducing their utility bills. Freddie Mac provides financing for energy-efficient changes with long-term mortgage payments (Freddie Mac, 2021). The recent

Freddie Mac report demonstrates that the homes, which are rated by different energy efficiency rating systems like HERS Index are sold more than the similar unrated houses. Indeed, the houses, which are rated better could be sold 3-5 percent more than the lesser-rated homes (Argento, et.al, 2019).

Appraising a high-performance home

In 2011, in response to growing concerns that standard appraisal forms are not set up to give adequate recognition to costly energy-conservation improvements the Appraisal Institute published "the Residential Green and Energy Efficient Addendum." The addendum that should be attached to any standard appraisal report covering a high-performance property requires the appraiser take notice of energy efficiency improvements and seek a value adjustment consistent with the local market conditions (Washington Post, 2011). The addendum relies on properly trained third-party professionals to test and report on the energy efficiency improvements used at home because very few appraisers are trained to complete the addendum accurately (Fincham, 2020). The third-party verification section is pre-filled with a few common certification organizations (EPA Energy Star, DOE Zero Energy Home, USGBC LEED, Living Building Certified, etc.) and energy labels (RESNET's HERS, DOE's Home Energy Score) to select from.

A 2015 appraiser-led study in Washington, D.C. found that homes with high-performing features sell for an average premium of 3.46% compared to homes without these features (Adomatis, 2015). A 2017 study on homes sold in Northern and Central Virginia found that the average price premium for a certified high-performance home was more than 5% when compared to non-certified homes (Adomatis, 2017). A 2018 study in the Bay Area found that high-performance homes with a third-party verification have, on average, a selling price 2.19% higher than non-certified homes (Adomatis, 2018).

The challenge for the appraisers is to calculate the value the energy efficient improvements bring to real estate transactions. In other words, if there is an added value associated with the sale of homes with high-performing features, how can the appraiser obtain the data and information required to calculate such a premium? The goal of this paper is to provide appraisers with a tool that could help them estimate the benefits of an energy efficiency measure and use it in their appraisals.

Methodology

In a previous study (Fenner, 2019), an energy model was developed for a 1204 SF baseline modular home in Climate Zone 2A (hot-humid climate). The baseline home was a one-story, 28 ft wide and 43 ft long with three bedrooms, two bathrooms, 8 ft ceiling height, and 4:12 gable roof located in Gainesville, Florida. Energy consumption of the baseline home was calculated using BEopt™ (Building Energy Optimization Tool). The BEopt™ is a computer program designed by the National Renewable Energy Laboratory to optimize energy efficiency models along the path to Zero Net Energy homes. In addition to Climate Zone and the baseline modular home characteristics (SF, width and length, ceiling height, number of bedrooms/bathrooms, and roof slope), the thermophysical and equipment properties of the house (orientation, R values for walls and roof, size and properties of windows, lighting fixtures, properties of air conditioning system, water heaters, and appliances) were needed to use BEopt™ 2.8.0 software. The output included the baseline construction cost and its annual energy consumption.

Next, the baseline home was upgraded with the following energy efficiency measures to meet the 2018 International Energy Conservation Code (IECC 2018):

- Increasing wall insulation from R-13 to R-21
- Increasing roof insulation from R-30 to R-38
- Reducing Ufactor and SHGC for windows from 0.35 and 0.44 to 0.34 and 0.30, respectively
- Reducing infiltration from 5 Air Change Per Hour at 50 Pa (ACH50) to 4.5 ACH50
- Increasing air condition SEER from 13 to 16
- Changing water heater from an electric standard to a 50-gallon Heat Pump Water Heater
- Changing lighting from 100% incandescent to 100% LED
- Changing the baseline appliances to EnergyStar appliances

BEopt™ was used for each EEMs individually (wall insulation, roof insulation, etc.) to identify the energy savings and costs associated with adding each EFMs. The next step was to use BEopt™ to simulate all features together to determine the total energy savings of the IECC 2018 home compared to the baseline home. Ultimately, by developing a spreadsheet the present worth of each EEMs was calculated considering the remaining life of the home, and the discount and energy inflation rates.

Under the cost analysis, the initial construction costs and the simple payback period were calculated. The initial construction cost refers to the costs associated with the materials, equipment, and labor needed to manufacture the baseline home and add each EEMs. The average national prices for materials and installation (R. S. Means 2019) were adjusted for the location of the house, Gainesville, FL. The literature and interview with manufacturers of modular homes revealed that materials cost for modular homes are 10% less than site-built residential homes due to bulk purchase. In addition, installation cost for modular homes is considerably less than site-built homes due to higher labor productivity (controlled environment, repetition of similar activities, and working on the factory floor rather than working at heights) and using more advanced tools and equipment. The decrease in labor cost reported varied as low as 33% and as high as 50%. For this study a 40% reduction in installation cost was considered.

The simple payback period refers to the time required to recover the project investment without considering the time value of money. It is often defined as the break-even point, i.e., the year at which initial investment is offset by the benefits accumulated, which in this case was the energy-associated costs.

Results and Discussion

The construction cost for the upgraded home is $70,967, which is $5,947 more than the baseline home. This results in a 7.2-year simple payback period, which means that the additional investment for upgrading all EEMs will return after 7.2 years due to the lower energy bills resulted from the upgrades. By using BEopt™ the annual energy consumption for the base home and upgraded home were found to be 9,894 kWh and 4,958 kWh, respectively. Table 1 shows the amount of annual energy savings (kWh/year), annual reduction in energy bill ($/year), construction costs, and simple payback period for each EEM.

A spreadsheet was developed to help appraisers estimate the value added to a home due to inclusion of an energy efficiency measure. This value is a function of the annual energy savings (kWh), electricity cost ($/kWh), energy inflation rate, discount rate, and the remaining life of the home. Table 2 shows the value added to the home of this study for each EEM considering electricity cost of $0.17 per kWh and energy inflation rate of 5%. The value added are shown for 10- and 20-year remaining life and discount rates of 1 to 5%. For example, by upgrading wall insulation from R-13 (2x4 stud at 16 in o.c.) to R-21 (2x6 stud at 24 in o.c.), an energy saving of $44 per year can be achieved (Table 1).

Table 1

Energy savings, costs, and simple payback period for each energy efficiency measure

EEM	Energy Savings (kWh/year)	Energy Savings ($/year)	Initial Cost $	Simple Payback (year)
Walls	260	$44	$405	9.2
Ceiling	114	$19	$403	20.8
Window	85	$14	$268	18.5
Infiltration	155	$26	$262	10.0
Water Heater	1,459	$190	$1,501	7.9
HVAC	1,831	$311	$2,429	7.8
Dishwasher	93	$16	$141	8.9
Clothes Washer	381	$65	$127	2.0
Refrigerator	61	$10	$19	1.9
Clothes Dryer	219	$37	$176	4.7
Lighting	791	$134	$216	1.6
All Measures	**4,891**	**$831**	**$5,947**	**7.2**

Assuming a discount rate of 3% and the remaining life of 20 years, the appraiser can increase the value of the home by $1,088 (Table 2). The values in Table 2 may be converted to dollar per square foot to allow use of the table for homes with three bedrooms, two bathrooms, and 8 ft ceiling height located in hot-humid climates.

Table 2

The value added to the home appraisal value due to implementation of energy efficiency upgrades for 10- and 20-year remaining life, discount rates of 1 to 5%, electricity cost of $0.17 per kWh, and energy inflation rate of 5%.

Parameters	Remaining Life = 10					Remaining Life = 20				
	1%	**2%**	**3%**	**4%**	**5%**	**1%**	**2%**	**3%**	**4%**	**5%**
Walls	$551	$520	$492	$466	$442	$1,363	$1,215	$1,088	$979	$884
Ceiling	$241	$228	$216	$204	$194	$597	$533	$477	$429	$388
Window	$180	$170	$161	$152	$145	$446	$397	$356	$320	$289
Infiltration	$328	$310	$293	$278	$264	$812	$725	$649	$564	$527
Water Heater	$3,090	$2,919	$2,761	$2,615	$2,480	$7,467	$6,820	$6,108	$5,493	$4,961
HVAC	$3,878	$3,663	$3,465	$3,282	$3,113	$9,597	$8,559	$7,665	$6,894	$6,225
Dishwasher	$197	$186	$176	$167	$158	$487	$465	$389	$350	$316
Washer	$807	$762	$721	$683	$648	$1,997	$1,871	$1,595	$1,435	$1,295
Refrigerator	$129	$122	$115	$109	$104	$320	$285	$255	$230	$207
Dryer	$464	$438	$414	$393	$372	$1,148	$1,024	$917	$835	$745
Lighting	$1,675	$1,583	$1,497	$1,418	$1,345	$4,146	$3,697	$3,611	$2,978	$2,689
All Features	**$10,359**	**$9,786**	**$9,256**	**$8,767**	**$8,315**	**$25,635**	**$22,862**	**$20,476**	**$18,415**	**$16,629**

Conclusions

Appraisers should consider the value added to homes due to energy efficient upgrades because they reduce energy consumption of the home and lower energy bills for homeowners. Fannie Mae, Freddie Mac and FHA guidelines require appraisers to consider the energy efficient features of the home and make an adjustment in the appraised value. However, energy efficiency can be overlooked in the appraisal process because of difficulties in determining the amount of added value. The approach used in this paper was to determine the energy savings and construction costs associated with energy efficiency measures implemented in a home using BEopt™ energy modeling software. The data then was used to determine present worth of the annual energy savings for the remainder life of the home considering the energy inflation and discount rates. This approach makes the process of estimating the value added of an energy efficiency measure easier for appraisers. The other benefit of this approach is providing the simple payback period for each energy efficiency measure to help homeowners decide which measure to choose.

The value-added numbers may be converted to dollar per square foot and used for small size homes in a hot-humid climate. However, for medium or large size homes and in other climate conditions, a separate energy modelling and cost analysis like the one performed in this study are needed to calculate the value-added due energy efficiency measures.

References

Adomatis, S. (2015). What is green worth. Retrieved from https://www.imt.org/wp-content/uploads/2018/02/HighPerformance_Home_Valuation_Report_Sept2015.pdf

Adomatis, S. (2017). Appraisers' Analysis of Pearl National Home Certification Sales Premiums. Retrieved from https://www.elevateenergy.org/wp/wp-content/uploads/Valuation-Study-of-Pearl-Certified-Homes.pdf

Adomatis, S. (2018). Green home sales prices in northern California. Retrieved from https://builditgreen.org/wp-content/uploads/2017/12/BIG_Green_Home_Sales_Prices_Report_FINAL_2018.pdf

Appraisal Institute. (2019). Appraised value and energy efficiency: Getting it right. Retrieved from https://www.appraisalinstitute.org/assets/1/29/AI-BCAP_Flyer.pdf

Argento, R., Fang Bak, X., & Brown, L. (2019). Energy efficiency: Value added to properties & loan performance. Retrieved from https://sf.freddiemac.com/content/_assets/resources/pdf/fact-sheet/energy_efficiency_white_paper.pdf

Athalye, R. A., Sivaraman, D., Elliott, D. B., Liu, B., & Bartlett, R. (2016). Impacts of model building energy codes (No. PNNL-25611-Rev1). Pacific Northwest National Lab. (PNNL), Richland, WA (United States). Retrieved from https://www.osti.gov/biblio/1334003

Burge, M. (2016). How energy-efficient upgrades can increase your home's value. Retrieved from https://www.nerdwallet.com/blog/mortgages/6-energy-efficient-upgrades-increase-home-value/

Doyle, V. and Bhargava, A. (2012). The Role of Appraisals in Energy Efficiency Financing, U.S. Department of Energy. Retrieved from https://www.nrel.gov/docs/fy12osti/54329.pdf

EnergySage. (2018). Residential energy efficiency: How to increase home value for appraisal. Retrieved from https://www.energysage.com/energy-efficiency/why-conserve-energy/residential-ee/

Fenner, A. E. (2019). Towards Hyper-Efficiency and Carbon Neutrality in Industrialized Residential Construction (Dissertation). University of Florida

Fenner, A. E., Kibert, C. J., Li, J., Razkenari, M. A., Hakim, H., Lu, X., Sam, M. (2020). Embodied, operation, and commuting emissions: A case study comparing the carbon hotspots of an educational building doi: https://doi.org/10.1016/j.jclepro.2020.122081

Fontinelle, A. (2019). What you should know about home appraisals. Retrieved from https://www.investopedia.com/articles/pf/12/home-appraisals.asp

GovTrack (2022). S. 4671: GREEN Appraisals Act of 2022. Retrieved from Text of S. 4671: GREEN Appraisals Act of 2022 (Introduced version) - GovTrack.us

Harney, K. (2011). Appraisers get guidelines for setting the value of energy-saving home improvements. Retrieved from https://www.washingtonpost.com/realestate/appraisers-get-guidelines-for-setting-the-value-of-energy-saving-home-improvements/2011/10/05/gIQAiZRkSL_story.html

Hewes, T., & Peeks, B. (2013). Northwest Energy Efficient Manufactured Housing Program: High Performance Manufactured Home Prototyping and Construction Development. Retrieved from https://digital.library.unt.edu/ark:/67531/metadc872175/

Homes, S. (2019). How do appraisals affect your mortgage? Retrieved from https://southdownhomes.com/how-do-appraisals-affect-your-mortgage-2/

Talbot, J. (2012). Mobilizing Energy Efficiency in the Manufactured Housing Sector. American Council for an Energy-Efficient Economy. Retrieved from https://www.workingre.com/wp-content/uploads/2013/08/Energy-Efficiency-Manufactured-Housing.pdf

Thompson, J. (2018). What does a house appraiser look for? Retrieved from https://homeguides.sfgate.com/house-appraiser-look-for-2828.html

U.S. Department Of Energy. (2016). Energy-efficient home design. Retrieved from https://www.energy.gov/energysaver/design/energy-efficient-home-design

U.S. Energy Information Administration (EIA), Monthly Energy Review (2021), Tables 1.3 and 2.1-2.6. Retrieved from https://www.eia.gov/totalenergy/data/monthly/pdf/flow/total_energy_2020.pdf

Williamson, J., & Palim, M. (2022). Appraising the Appraisal: A Closer Look at Divergent Appraisal Values for Black and White Borrowers Refinancing Their Home. Washington, DC: Fannie Mae, 500. Retrieved from https://www.fanniemae.com/media/42541/display

Mitigation measures to prevent delays in Construction Industry using 3D Printing

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Project delays are a significant challenge that can significantly impact construction projects and have been a problem affecting construction projects for more than a century. 3D Printing can reduce the probability of project delays due to its ability to work in inaccessible areas, its greater product customization, minimized waste production, and its ability to print intricate designs. Therefore, given the capabilities of 3D Printing, the research aims to identify the advantages and limitations of 3D Printing Technology. These main causes are delaying the projects and finding a way to mitigate the project delays using 3D Printing Technology. The study used a survey methodology, the literature Review for the recently published papers on 3D Printing and Project Delays. As per this study, the main reason for the project delays are the inappropriate project schedule and labor issues, whereas 3D Printing helps finish the intricate designs, reduces human errors and greater customization makes this technology stand on top. Despite the benefits, this study also identified the barriers to implementing this technology on the construction site: high initial investment and unavailability of standard regulations and codes.

Keywords: Project Delays, 3D Printing, Technology, Additive Manufacturing, Benefits, Challenges.

Introduction

Construction project delays have historically been a critical concern in the construction industry (Morris and Hugh, 1988). Completing projects before the completion date benefits all project stakeholders. However, delayed projects can have consequential impacts on project stakeholders, including the owners and contractors. For the owner, losses can be in the form of delayed project start and loss of revenue, and contractors can also be impacted tangibly and intangibly in the form of the penalty of non-engaged labor, equipment standby charges, fees on disturbing material and equipment timetables, reputation loss and others (Ojoko et al., 2016). Project delays can appear to be an unavoidable event in the delivery of building projects (Ojoko et al., 2016), but it may be efficiently controlled or managed when their causes are carefully recognized and examined. Completing projects as per the schedule can indicate efficiency, at the same time, uncertainties from stakeholders and other contextual factors (such as resources, engagement of other parties, contractual interactions, and others), along with the unpredictable nature of the industry, can impact a project's schedule (Assaf & Al-Hejji, 2006). Further, the top factors associated with delays were identified as ineffective project planning and scheduling, poor site management, and supervision, poor financial control on-site, and rework due to errors (Aziz, 2013). Using technology in the form of three-dimensional (3D) Printing can alleviate the impacts of some of the factors (such as poor site management and supervision and rework due to errors) that contribute to the delay of a project. 3D Printing, called Rapid prototyping or Additive Manufacturing, is a sophisticated manufacturing technology that can autonomously manufacture complicated form geometries from a 3D computer-aided design model without tooling, dies, or fixtures (Tay et al., 2017). Indications exist that the technology has made inroads into construction sites (Perkins & Skitmore, 2015). However, it is unclear how 3D Printing can contribute to mitigating the delays often cited in the literature.

Therefore, the research determines the questions mentioned in the following:
1. What are the project delays in the construction industry?
2. What are the main causes for the Project delays?
3. What are the advantages and disadvantages of 3D Printing technology?
4. Does the 3D Printing Technology help the projects to mitigate the delays incurred in the project?

Literature review

Weather conditions such as extreme temperatures, precipitation, and high winds were recognized as the most impacting weather conditions on construction (Schuldt et al., 2021). Along with exogenous circumstances, technical and project management considerations such as material shortages, labor supply, equipment failures, ineffective communication between stakeholders, and errors during construction can also potentially cause delays (Hamzah et al., 2011). Further, client and contractor-related factors can also contribute to delays which emanate majorly from delays in interim payment, change orders, poor planning, scheduling, monitoring, feedback, communication and coordination, delay in material availability, inadequate essential materials, and others (Ojoko et al., 2016). According to Al-Momani (2000), the primary reasons for delays in public project development include designers, user changes, weather, site circumstances, late delivery, economic constraints, and a rise in quantity. These characteristics influence the successful delivery of projects within the time frame provided in the agreement (Al-Momani, 2000). As per Assaf and Al-Hejji (2006), owners and consultants recognize that assigning to the lowest bidder is the most common source of delay. However, contractors believe that the most severe reasons for delay are connected to owners. Assaf and Al-Hejji (2006) explained that only one source of delay is shared by all parties: changing orders by the owner during construction. Many factors are shared by the parties involved, such as progress payment delays, improper planning and scheduling by the contractor, poor site management and supervision by the contractor, labor shortages, and financial challenges by the contractor. Both owners and consultants identify labor and contractor-related issues as acute and significant drivers of delay, whereas contractors identify owners and consultants as significant contributors to delays in construction projects is identified by (Assaf & Al-Hejji, 2006). Thus, project delays can be attributed to various controllable and uncontrollable factors which include weather, labor shortages, economic conditions, selection criterion for contractor selection, owner change orders, poor site management supervision, rework because of poor quality of work, and others.

Given the numerous anticipated and unanticipated parameters that can cause project delays, numerous strategies have been recommended in the literature to alleviate the impacts of the factors on the project's schedule. For example, to counter the impact of weather, three distinct weather modeling strategies for reducing uncertainties in construction have been recommended that include the generation of weather models, construction effect models, and project scheduling models, along with obtaining historical weather pattern information for using these concepts since it assists in establishing mitigation and adaptation approaches (Schuldt et al., 2021). Weather simulation models should not assume that the weather parameters are constant and can provide input to weather effect models, which in turn provide input to construction schedule models (Schuldt et al., 2021). Rapid construction is possible with 3D Printing. Construction moves along considerably more quickly than it did with earlier technologies. Using 3D Printing technology, construction time may be significantly decreased. For instance, 3D Printing enabled the production of a structural wall in 65 hours as opposed to 100 hours (El-Sayegh et al., 2020). The delivery time for products that require expedited delivery is eliminated by 3D Printing. Thus, this approach enhances production that would otherwise be reduced as a result of late deliverables. (El-Sayegh et al., 2020) In addition to lowering labor expenses, 3D Printing also lowers the time and price of installing and removing formwork.

Along with these technological approaches, 3D Printing can control some of the aspects relating to site management, material, labor, and work quality which can cause delays in a construction project. 3D Printing can also assist in reducing some of the significant issues of a building project, such as construction planning and monitoring, efficient communication, safety, and procurement management, by using BIM, as explained by (Tay et al., 2017). Along with these benefits, several advantages of using 3D Printing have been documented, including decreased waste, design flexibility, and reduced personnel (Wu et al., 2016a). The usage of 3-D Printing in the construction sector is heavily reliant on the accuracy of the Printing tasks, the existence of Printing materials, the budget of the Printing process, and the Printing duration, all of which influence the selection of applicable 3-D Printing technologies as per (Wu et al., 2016). Further, 3D Printing and automation for Building & Construction improvement would be ideal as they can eliminate or reduce human engagement in potentially risky operations, thereby eliminating the risk involved in these dangerous tasks. Thereby indicating that the labor engagement or use of unskilled labor will decrease with increased adoption and implementation of 3D Printing (Tay et al., 2017). Finally, the building design (shape and massing) will no longer be a barrier, and complicated designs can be created within the timeframe (Tay et al., 2017). At the same time, numerous challenges exist for 3D Printing to be used. The current ineptness of automation for truly large-scale fabrication, the severely limited scope of materials that can currently be used in construction, the high price that the industry's pioneers would have to pay in simple things like training, organization, and management, as well as the price of the equipment itself, are all prohibitively for its implementation (Pessoa et al., 2021). According to Wu et al. (2016b) the application of 3-D Printing in the construction sector is still in its infancy, and the life cycle performance of the printed projects is unknown, despite the fact that the usage of BIM may assist in investigating the printed goods at the shape, performance, and assembly levels. The future of additive manufacturing in the construction industry looks interesting, but according to (Camacho et al., 2017), more interdisciplinary research is needed to develop new materials, processes, faster Printing, quality assurance, and mechanical property data before Additive Manufacturing (AM) can reach its full potential in infrastructure construction.

Thus given the importance of reducing human labor, better site, and project coordination, and the ability of 3D Printing to alleviate the potential impacts of factors on project delays, this research determines the main reasons for project delays and investigates whether employing 3D Printing can assist in offsetting some of the variables that are generating construction site delays.

Research Method

Given the research aimed to find out which factors primarily cause delays and to identify what are the ways that can help mitigate it through the usage of 3D Printing, they used a survey method as it has the ability to identify and determine the trends at the point of the study. The research used an online survey method as most have internet access, a likelihood of prompt responses (Flaherty et al., 1998), and studies within the construction industry have used the method to determine technologies (Langar and Fountain, 2018; McGraw Hill 2015). The general population of the study was US construction industry professionals possessing knowledge of 3D Printing technology and how it can solve the problems associated with project delays. The online instrument was generated in Qualtrics and consisted of both multiple-choice and open-ended questions. The survey consisted of three sections, including a) respondent demographics; b) 3D Printing implementation; c) the role of 3D Printing in helping mitigate the project delays. The survey questions were designed in such a manner that the respondents could complete the study within 10 minutes. After the instrument development, it is shared with professionals through LinkedIn, Email, and as a reminder again sent to professionals after a week. These professionals are targeted as 3D Printing experts. The questionnaire was sent to 20 professionals and received 11 responses. Therefore, the percentage of respondents was 55%.

Results

The majority (40%) of the respondents identified themselves as consultants, followed closely by researchers (30%), as indicated in Figure 1. 36% of others are working in the manufacturing/supply chain/designer business. 40% of respondents are into the form of residential construction, as per Figure 2. The majority of the respondents were in the age group of 25-34 years (Figure 3). 50% of respondents had 1-5 years of experience in the construction industry, and 30% had about 5-10 years of experience in the construction industry (Figure 4). 60% of companies have a company size of less than 100 employees. 10% are into 1,000-1,500 employer companies, and 20% have greater than 2,000 employees (Figure 5). 50% of respondents replied that the revenue of the companies of the respondents is less than $10,000,00 (Figure 6).

Figure 1: Role of Respondents

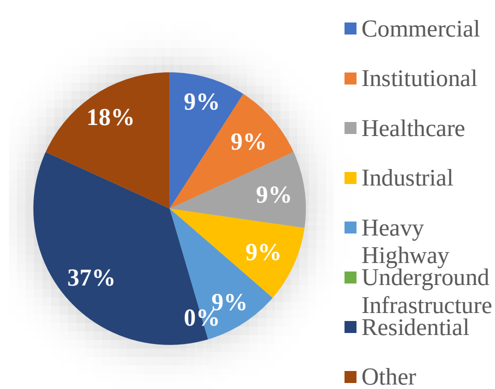

Figure 2: Form of construction

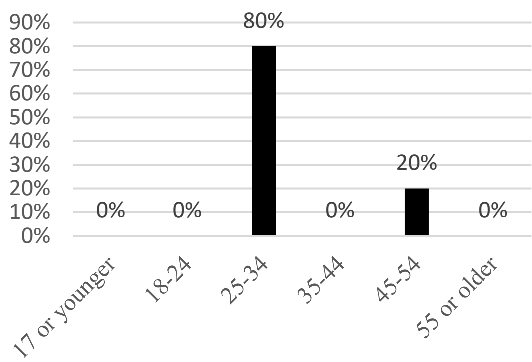

Figure 3: Age of the Respondent

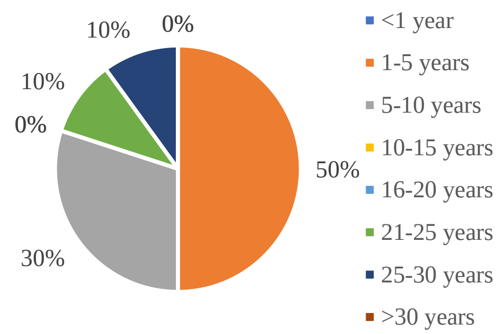

Figure 4: Respondent work Experience

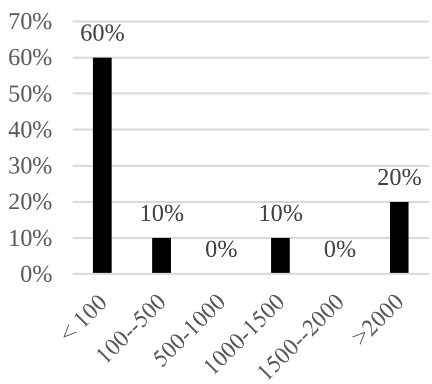

Figure 5: Employees in Company

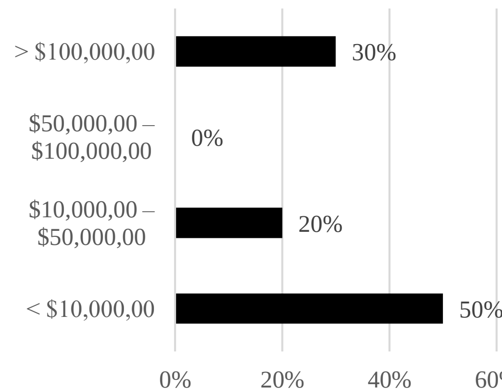

Figure 6: Company size based on revenue

Project Delays

Per the survey respondents, the main reason for project delays included labor shortages, project complexity, inadequate planning, and inappropriate project scheduling (Figure 7).

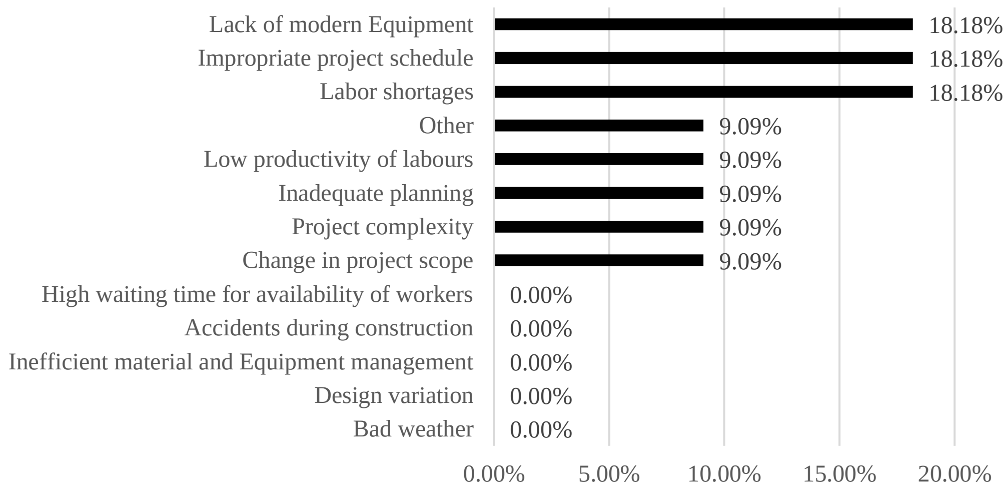

Figure 7: Main cause for the Project Delays

Additive Manufacturing

The majority of the respondents (80%) haven't implemented 3D Printing. Currently, 3D Printing applications are in the initial stage and getting implemented gradually. It also consists of barriers such as high initial investment and training required. As per the respondents, design complexity was one of the most significant advantages of using 3D Printing (Figure 8). The equipment's initial investment was identified as the significant barrier to its implementation (Figure 9).

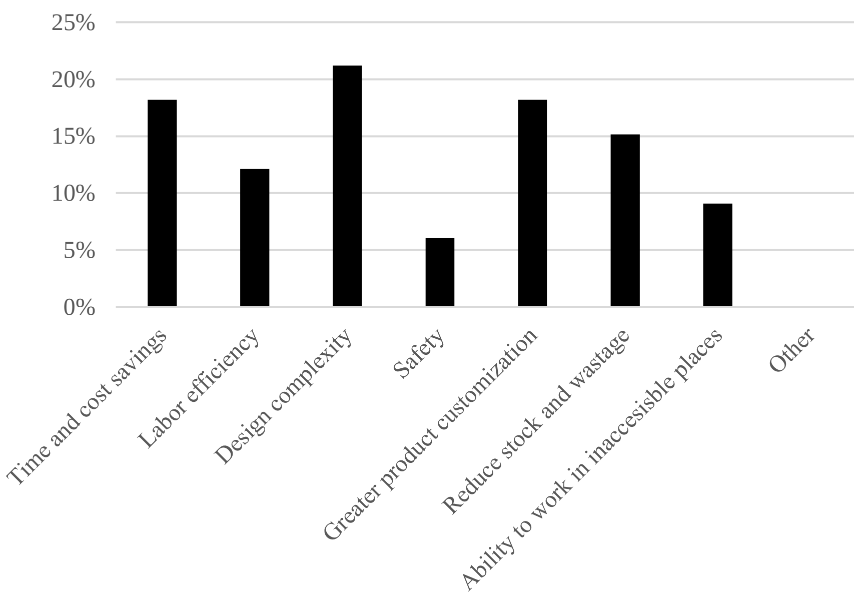

Figure 8: Advantages of 3D Printing

According to the survey, the limitation of 3D Printing is the initial investment, as the equipment is expensive (Figure 9). The respondents also identified that the extent of customization that can be done using 3D Printing is also effective, as shown in (Figure 10).

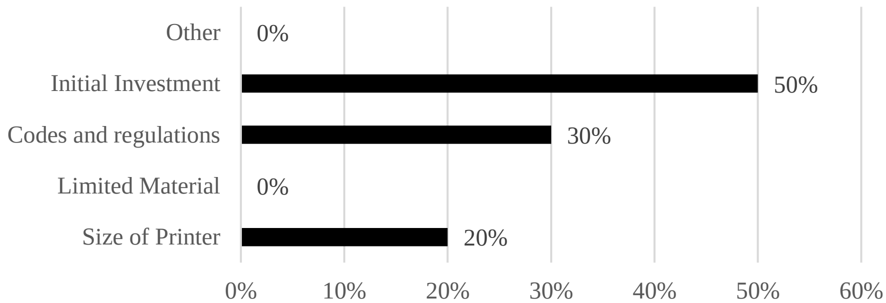

Figure 9: Barrier to Implementation of 3D Printing

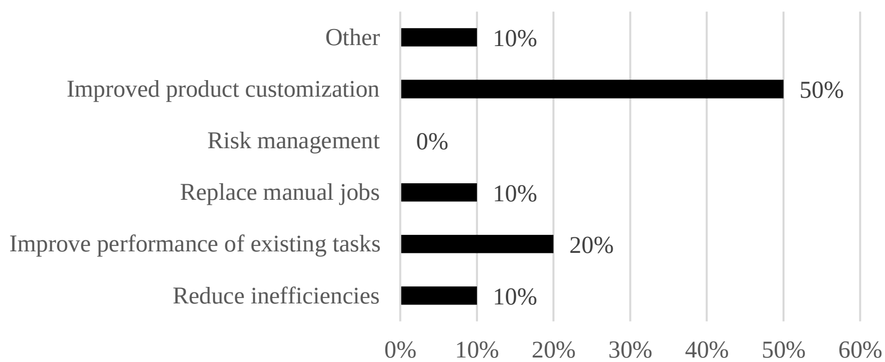

Figure 10: Effectiveness of 3D Printing

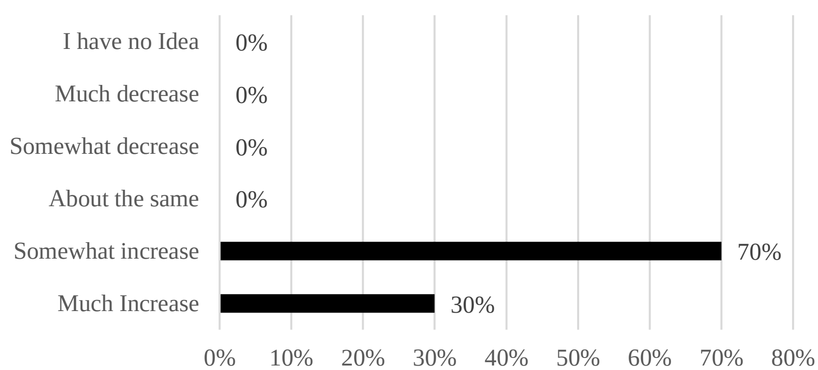

Figure 11: Future forecast of 3D Printing

The future forecast of 3D Printing, as per the survey shown in Figure 11, is 70% mentioned somewhat increase, and 30% mentioned much increase. For the question of whether the delay can be mitigated or not, more than 50% have mentioned probably and definitely yes that delay can be mitigated using 3D Printing in construction projects (Figure 12).

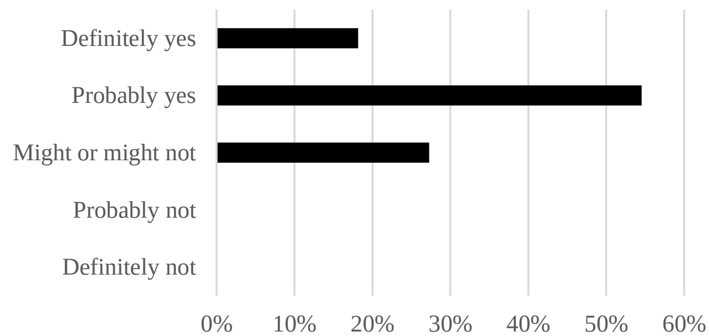

Figure 12: Delay mitigation through 3D Printing

Summary and conclusion

3D Printing is one of the emerging technologies in the construction industry. The construction industry will undergo a transformation due to 3D Printing. Construction might become more productive and sustainable with the help of Industry 4.0 advancements and 3D Printing. Project delays can occur due to various reasons, but some of the reasons, like labor shortage, Project complexity, and delay due to human errors, can be mitigated of some sort with 3D Printing. 3D Printing is good at customizing the designs, whatever we like, and helping to finish the intricate designs that are complicated to do manually or with current procedures and providing us with a prototype that is shown digitally in 3D. Though this has all these advantages, it also contains some of the limitations that stop the adoption of this technology, such as the high initial investment, No proper standard codes, and regulations. The delay mitigation can be done using this 3D Printing technology. However, there must be further research on providing standard codes and regulations. If these limitations can be overcome, this 3D Printing will serve the world with its applications in the construction industry.

Future studies

This research can be extended by standardizing the codes and regulations required for more knowledge on using 3D Printing. Research is needed on this technology and whether it can be integrated with BIM software to improve its applications. Research can also be done on introducing multiple nozzles and safety monitoring systems to enhance the safety of using this technology on-site.

References

Al-Momani, A. H. (2000). Construction delay: a quantitative analysis. International Journal of Project Management, 18(1), 51-59.

Assaf, S. A., & Al-Hejji, S. (2006). Causes of delay in large construction projects. International Journal of Project Management, 24(4), 349-357.

Camacho, D. D., Clayton, P., O'Brien, W., Ferron, R., Juenger, M., Salamone, S., & Seepersad, C. (2017). Applications of additive manufacturing in the construction industry–a prospective

review. Paper presented at the ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction, , 34
El-Sayegh, S., Romdhane, L., & Manjikian, S. (2020). A critical review of 3D printing in construction: Benefits, challenges, and risks. Archives of Civil and Mechanical Engineering, 20(2), 1-25.
Faherty, T.B., Honeycutt, E. D., Powers, D. (1998). Exploring text-based electronic mail surveys as means of primary data collection, Proceedings of the 1998 Academy of Marketing Science Annual Conference, Norfolk, VA, USA, 260–264
Fountain, J., and Langar, S. (2018). "Building Information Modeling (BIM) outsourcing among general contractors." Automation in Construction, 95, 107-117
McGraw Hill. (2015). Measuring the impacts of BIM on Complex Buildings: SmartMarket Report.
Morris, P. and Hough, G. (1988). The Anatomy of Major Projects. John Wiley and Sons Ltd, New York,1st Edition.
Pessoa, S., Guimarães, A. S., Lucas, S. S., & Simões, N. (2021). 3D printing in the construction industry - A systematic review of the thermal performance in buildings. Renewable and Sustainable Energy Reviews, 141, 110794. https://doi.org/10.1016/j.rser.2021.110794
Schuldt, S. J., Nicholson, M. R., Adams, Y. A., & Delorit, J. D. (2021). Weather-related construction delays in a changing climate: a systematic state-of-the-art review. Sustainability, 13(5), 2861.
Wu, P., Wang, J., & Wang, X. (2016). A critical review of the use of 3-D printing in the construction industry. Automation in Construction, 68, 21-31.

Life-Cycle Assessment of a Concrete Pedestrian Bridge: A Comparative Analysis of 3D Printing and Precast Techniques

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This study aims to compare the environmental impact of precast and 3D concrete printing (3DCP) techniques with a pedestrian bridge case study. A detailed cradle-to-site life cycle assessment has been performed from the standpoint of material, construction, and installation stages. The results showed that the concrete used in 3DCP has a higher negative environmental impact compared to the precast method due to the higher percentage of cement used in printable concrete. However, since C3DP used less material than the precast technique, there is no significant difference in the environmental impact of the total concrete used between the 3DCP and precast bridges. In addition, due to the use of reinforcement and formwork in the precast technique, the environmental impact of the total materials used in the precast bridge was more adverse than the 3DCP bridge. Notably, due to using electricity for printing, the negative environmental impact of the construction process in 3DCP was significantly higher than in the precast technique. Finally, the total carbon dioxide equivalent emitted during the construction of the 3DCP bridge was 80% of the precast bridge.

Key Words: LCA, Environmental Impact, Concrete, Bridge, 3DCP

Introduction

The environmental impact of buildings' construction and operation is enormous. The built environment contributes 40% of global energy consumption, 28% of global greenhouse gas (GHG) emissions, 12% of global potable water consumption, and 40% of solid waste creation (Agustí-Juan and Habert 2017). Concrete and cement-based products are at the heart of the building industry, and their use has expanded exponentially in recent decades (Scrivener, John, and Gartner 2018). Concrete production has a significant carbon footprint, accounting for 4-5% of global CO_2 emissions (Zhang et al. 2014). Furthermore, in concrete construction, a substantial amount of waste is usually generated, mostly from formwork wastes (Mohammad, Masad, and Al-Ghamdi 2020). It has previously been demonstrated that conventional casting technologies have a very low carbon footprint compared to concrete. In particular, the contribution of concrete processing (i.e., transportation, mixing, and pumping) has been less than 1% of concrete's environmental impact (Kuzmenko et al. 2022). Furthermore, concrete shaping through the use of standard formwork along with on-site energy consumption was shown to represent less than a couple of percent of concrete's environmental impact (Hong et al. 2015). The low contribution is due to the low-tech and low-energy nature of these processes and the high reuse rate of casting equipment such as forms.

Over the past few decades, there has been an increasing interest in automated construction. The present work is focused on extrusion-based additive manufacturing with cement-based materials, referred to as 3D Concrete Printing (3DCP). 3DCP consists of a successive layer-by-layer stacking of concrete filaments contouring an object with no formwork, i.e., by direct material placement. It is thus usually associated with a vision of a so-called "free-form construction" (Tuan et al. 2018). The 3DCP technology, developed around 20 years ago (Khoshnevis 2004), offers potential constructability benefits, including reduced waste, design freedom, reduced human error, and fast production in construction projects (Davtalab et al. 2022). However, limited studies are focusing on sustainability performance and the environmental impact of this new technology (Tuan et al. 2018; Liu et al. 2022).

The adoption of 3DCP in the construction sector was accelerated in recent years. Although there are several applications of 3DCP technology in building construction (Tuan et al. 2018), the use of this technology in bridge construction is still at a primitive stage. C3DP technology has been used for small bridge construction in a few demonstration projects in different countries, mainly pedestrian and bicycle bridges (see Table 1). Detailed information on these bridges can be found in the work of (Miryousefi Ata, Kazemian, and Jafari 2021). Concrete 3D printing allows for a great deal of geometric customization, allowing the bridges to have various expressions (Tuan et al. 2018). It may be possible to use 3D-printed elements in a circular economy since they can be printed, mounted on-site, clamped together and tensioned, and then disassembled anytime to be reused or recycled (Tuan et al. 2018). Although 3DCP is in the early stages of commercialization, the rapid advancements made in this technology indicate its great potential for automating bridge construction in the near future.

Table 1

A summary of 3D Printed Bridges

No	Year	Location	Robotic Printer	Length	Width	Reference
1	2016	Spain	Gantry Printer	8 m	1.75 m	(Mechtcherine et al. 2018)
2	2017	Netherland	Gantry Printer	8 m	3.5 m	(Wolfs and Suiker 2019)
3	2019	United States	Gantry Printer	10 m	0.9 m	(Buswell et al. 2018)
4	2017	China	Robotic Arm	26.3 m	3.6 m	(Xu et al. 2020)
5	2020	Belgium	Robotic Arm	27 m	3 m	(Vantyghem et al. 2020)

This study aims to perform a comparative Life Cycle Assessment (LCA) to investigate the environmental impact of two construction methods, 3DCP and precast, using a bridge construction case study. This study mainly focuses on greenhouse gas emissions from the material extraction and during the construction phase, using a cradle-to-site LCA. The case study is an 8-meter-long, 3.5-meter-wide pedestrian bridge built in 2017 in the Netherlands (known as the 3DCP bridge). For the construction of this bridge, a novel method was used for integrating steel wire reinforcement into the print filament. In addition, a bridge with the same geometry is designed based on the cast-in-place concrete box girder technique (known as the precast bridge). Separate system boundaries are designed based on the construction methodology of each bridge to be used in LCA. Both the 3DCP and precast bridges are modeled in OpenLCA, an open-source software, for a detailed life cycle assessment. The results of this study contribute to the relatively new and understudied field of 3DCP by providing a detailed environmental impact of the material and construction process of a 3D-printed small-scale bridge. It also highlights the importance of adopting 3DCP technology with more sustainable printable concrete.

Literature Review

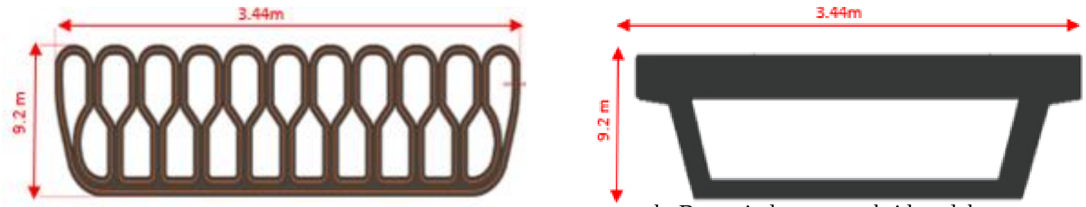
Although there have been numerous studies on 3DCP, the environmental impacts of this technology in construction have remained insufficiently explored (De Soto et al., 2018). A few studies have investigated the environmental impacts of 3DCP technologies using different projects and LCA methods. For example, Weng et al. (2020) evaluated prefabricated bathroom units using several construction techniques and found that 3DCP had lesser environmental impacts due to formwork-free construction. Alhumayani et al. (2020) performed a comparative LCA to compare the environmental impact of a load-bearing 3DCP wall with a reinforced cast-concrete wall and found out that the 3DCP wall has 27.2% higher GHG emissions due to the amount of cement used to produce printable concrete. Mohammad et al. (2020) conducted LCA on four load-bearing wall case scenarios of conventional concrete, 3DCP with reinforcement elements, 3DCP without any reinforcement, and 3DCP without any reinforcement and utilizing a lightweight printable concrete material. They concluded that 3DCP reduced environmental effects in terms of global warming potential as compared to conventional construction methods. Furthermore, Faludi et al. (2015) compared the environmental impacts of two types of additive manufacturing machines versus traditional numerical (CNC) milling machines and showed a reduction in energy use and waste in additive manufacturing machines. With respect to the contribution of the above studies, a comparative assessment is lacking to evaluate the environmental performance of the 3DCP and precast technique in terms of constructing a small-scale bridge. Therefore, this work has been conducted to fill the research gap by investigating the environmental impact of these two construction methods using a bridge construction case study.

Case Study

A small-sized concrete pedestrian bridge is used as a case study in this paper. The bridge was built in 2017 at the university of Eindhoven University of Technology (TU/e) using extrusion-based additive manufacturing with cement-based materials. The bridge was built using a gantry printer. In this gantry printer system, concrete was mixed with water and pumped into a hose by a mixer pump located on the side of the set-up. The hose was connected to the printer head situated at the end of the vertical arm of a motion-controlled 4-degree-of-freedom (4DOF) gantry robot serving a print area of 9 × 4.5 × 2.8 m (Bos et al. 2016). The total bridge dimensions are 8 m in length and 3.5 m in width, featuring 535 printed layers, with a length of 25.1 m of printing for each slab (a total printing path length of 13.4 km). The total printing time was 48 hours. With an average estimated power of 7kWh for a typical 4DOF gantry printer, a total of 336 kW of electricity is estimated for the printing process. The 3DCP technology used in this bridge features a reinforcement technique for extrusion-based 3DCP longitudinal filament by directly entraining a high-strength steel wire into the filament, actively fed from a spool by a small servo motor with an appropriately flexible cord (Bos et al. 2017). This technique allowed a fully automated process that does not reduce the geometrical possibilities of the 3DCP technology (Bos et al. 2017). The printing procedure, final slabs, and final bridge are shown in Figure 1.

Figure 1. The case study bridge and printing process at TU/e (Bos et al. 2017)

To compare the C3DP technique with the precast method, a similar bridge was designed based on the cast-in-place post-tensioned concrete box girder technique. The designed precast bridge had the exact geometry as the C3DP bridge and was designed based on the American Association of State Highway and Transportation Officials (AASHTO 2022) standard. The slab layout and dimensions of the designed precast bride and the C3DP bridge are shown in Figure 2. The total concrete used for both bridges is calculated based on the measurements: the 3DCP bridge requires 11.7 m^3 of concrete, which is 76% of the concrete needed for the precast bridge (15.3 m^3 of concrete). In addition, material wastage is considered in this study, which is typically between 1% and 13% of the total concrete required in conventional methods based on the type of project (Tam, Shen, and Tam 2007; Formoso Carlos et al. 2002). The concrete waste percentage can be calculated as the ratio of the volume of concrete purchased to the volume of concrete measured from the project drawing (Kazaz et al. 2015). The literature suggests an average of 9% waste for the precast technique, while this number can be up to 50% less in 3DCP. Based on the TU/e reports, the total waste calculated for the 3DCP bridge is around 6%. Assuming 33% less waste in the C3DP bridge compared to the precast bridge, the total volume of concrete required for the case study is estimated to be 12.4 m^3 and 16.7 m^3 for the C3DP and precast bridges, respectively. It illustrates that the concrete needed for the C3DP bridge is around 74% of the precast bridge.



a. 3DCP bridge slab (Salet et al. 2018)　　b. Box grinder precast bridge slab

Figure 2. The designed slab for the box grinder precast and 3DCP bridge slab

In addition to the amount of concrete required, the types of concrete used in the studied bridges differ. The concrete used in 3DCP usually has stricter requirements for fluidity, extrudability, and printability; The printing material not only needs to have enough fluidity to ensure the smooth pumping of the material and continuous extrusion from the nozzle, but also needs more water retention to avoid the clogging of the pumping tube due to material segregation. It also needs to have enough hardening speed to maintain the stable accumulation of subsequent layers to build (Lyu et al. 2021). For the 3DCP bridge, the printable material developed by SG Weber Beamix was used, comprising Portland cement (CEM I 52,5 R), siliceous aggregate with an optimized particle size distribution, and a maximum particle size of 1 mm, a small amount of polypropylene fibers for reducing crack formation due to early drying, and added accelerators (Bos et al. 2016; Kuzmenko et al. 2022). For the precast bridge, an M40 grade concrete, applicable to most precast slabs, is assumed with a compressive strength of 40 N/mm^2. The concrete mixture used in 3DCP and precast bridges are shown in Table 2.

Table 2

Concrete properties and volumes for 3DCP and precast bridges

3DCP Bridge Components	**1m^3 Concrete (Kg)**	**Whole Bridge (Kg)**	**Precast Bridge Components**	**1m^3 Concrete (Kg)**	**Whole Bridge (Kg)**
Cement: CEM I	540.0	6,697	Cement	400.0	6,671
Silica Fume	480.0	5,953	Coarse Aggregate	1,006.0	16,777
Sand	1,033.0	12,811	Fine Aggregate	800.0	13,342
Free Water	212.0	2,629	Free Water	180.0	3,002
Superplasticizer	8.8	109	Superplasticizer	2.0	33
Accelerator	6.0	74			
Polypropylene fibers	1.2	15			
Total Weight	*2,281.0*	*28,289*	*Total Weight*	*2,388.0*	*39,825*

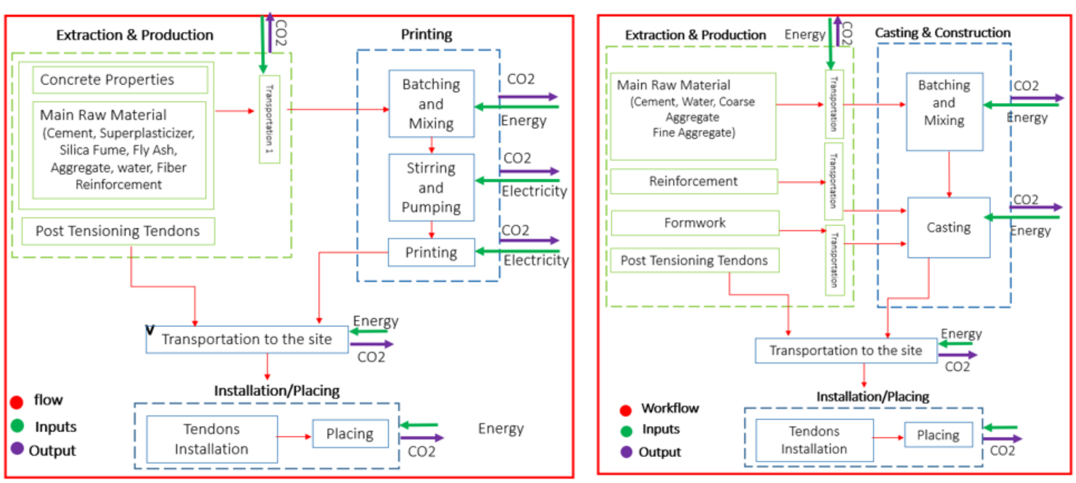
In addition to the type and amount of concrete, the type and method of reinforcement are different in the 3DCP and precast bridges. For the 3DCP bridge, high-strength steel Bekaert Syncrocord wires were used for reinforcement. Compared to ordinary reinforcement steel, the ductility of steel wires is limited. Wires with a diameter of 0.97 mm were considered for the 3DCP bridge (Bos et al. 2017). The total steel wire is calculated based on the total printing length (13.4 km) and specific weight of 7850 kg per m^3 for the steel wire (a total of 6.6 kg). On the other side, the specifications required by the American

Society for Testing and Materials (ASTM) are used to design the reinforcement needed in the precast bridge. In precast concrete, the maximum quantity of steel required for a 1 m^3 concrete slab is typically 1.5%, resulting in a total of 118 kg of steel reinforcement in this study. This value is significantly higher than the total of 6.6 kg steel wire required for 1 m^3 of 3D-printed concrete. Finally, a Post-tensioning technique with 16 Dywidag-system tendons was applied to the bridge with the prestress to an initial load P0 of 150 kN (Salet et al. 2018) is assumed for both bridges.

Research Methodology

LCA has become an essential tool for minimizing the environmental impacts of construction and enabling the construction sector to move toward sustainability (Fenner et al. 2018). LCA methods can assess and enhance the construction processes by taking a comprehensive and systemic approach to environmental assessment. Depending on the level of assessment required, there are several approaches to LCA in construction, including cradle-to-gate, cradle-to-site, cradle-to-grave, and cradle-to-cradle (Zheng and Chini, 2017). The present research methodology is based on the environmental LCA method framed by the international standards ISO 14040 (ISO, 2006). Following the LCA methodology presented in Yan et al. (2010), A cradle-to-site LCA was performed that included raw material extraction, bridge construction (precast vs. 3DCP), and installation for the studied bridges. First, the system boundaries and function units are defined for the LCA analysis. Then, several inventory data were collected using OpenLCA, open-source and free software for sustainability and life cycle assessment. Although various environmental impact categories are considered in this study, the main focus was given on Global Warming Potential (GWP), a measure of how much energy the emissions of 1 ton of a gas will absorb over a given period of time, relative to the emissions of 1 ton of carbon dioxide (CO_2). In this study, A carbon dioxide equivalent (CO_2-eq) metric is used to compare the emissions from various GHG on the basis of their GWP.

For each designed bridge, a separate system boundary was defined in this study (see Figure 3). Three main stages of the construction process for cradle-to-site LCA were considered in this study (1) material extraction, (2) construction, and (3) placing and installation. To compare the two bridges, similar values are assumed for most of the inputs, including the material transportation distance, water resources, and post-tensioning procedure.



a. 3DCP bridge construction *b. Precast bridge construction*

Figure 3. The designed system boundaries for the construction of the case study bridges

The estimated inputs in the defined system boundaries were modeled in OpenLCA. All the required inventory was selected from the EcoInvent 3.2 cut-off database within OpenLCA. Following the same method used by Agustí-Juan and Habert (2017), a ReCiPe Midpoint calculation method is used for the environmental impact calculation for each bridge (GreenDelta 2020). In addition, the IPCC 2013 GWP 100a method, based on data published by the Intergovernmental Panel on Climate Change, was selected as the environmental assessment method.

Results and Discussion

First, the GPW impact analysis was performed using generated CO_2-eq amount based on the concrete used in each bridge. The results showed that the extraction of the materials needed for 1 m^3 of concrete would result in generating 425 kg and 315 kg of CO_2-eq for 3DCP and precast bridges, respectively. In both scenarios, the contribution of cement to GWP impact is 85%. Figure 4 shows the LCA result regarding the GWP impact assessment of the concrete used in the case study. With respect to the GWP impact of 1 m^3 of concrete, the results indicated that the concrete mixture used in 3DCP generates 35% more CO_2-eq compared to the concrete mixture used in the precast bridge. The main reason is the higher amount of cement used in the 3DCP concrete mixture (almost 35% more cement compared to the precast concrete mixture). Because of the significant impact of cement production on generated GHG, it can be concluded that printable concrete with a high amount of cement would not be environmentally sustainable. In addition, the results showed that the 3DCP technique could reduce the concrete needed for the same bridge by 35% compared to the precast method in this case study. Therefore, as Figure 4 illustrates, the GWP impact of the total concrete used in each bridge does not significantly differ; i.e., the lower materials and lower waste associated with the 3DCP technique can even out the adverse environmental impact of the higher cement used for construction.

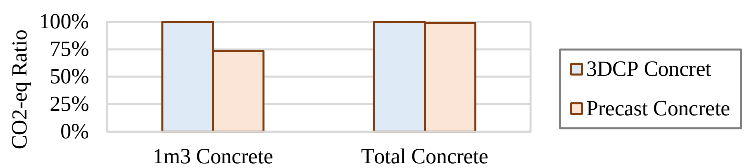
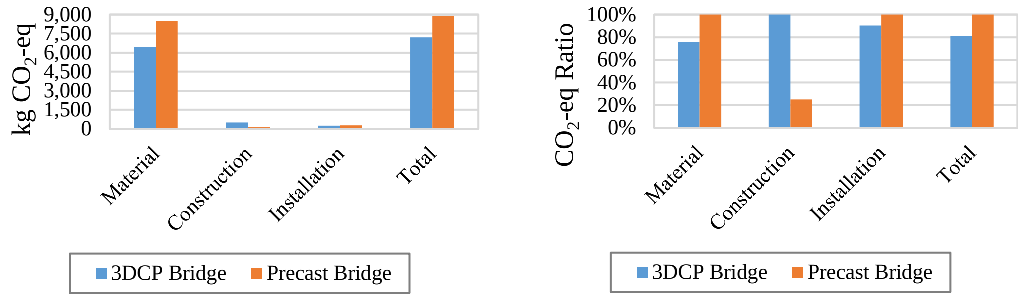


Figure 4. The GWP impact assessment of concrete used in the case study

Figure 5.a illustrates the amount of CO_2-eq generated in the bridge construction using 3DCP and precast methods. As the results show, the contribution of material extraction to total CO_2-eq generated is significantly higher than the construction and installation stages in both 3DCP and precast bridges (89% and 95% of total CO_2-eq emissions come from the material extraction in 3DCP and precast bridges, respectively). In addition, Figure 5.b shows the ratio of the generated CO_2-eq in each stage in both 3DCP and precast bridges. As the results show, the GWP impact of the total materials used in the 3DCP bridge is 76% of the precast bridge. Although the amount of CO_2-eq generated from the extraction of concrete components was almost the same in both scenarios, the higher volume of reinforcement materials in the precast bridge (compared to steel wire in the 3DCP bridge) significantly increased the generated CO_2-eq. In addition, even though the 3DCP is a free-form technique, the precast method requires formwork, which increases the GWP impact. Regarding the construction stage, it is shown that the GWP impact of the 3DCP technique is four times higher than the precast method. Although both techniques require energy to be consumed for transportation, batching, mixing, and pumping concrete, the C3DP technique needs a significant amount of electricity for the 3D printer. The higher amount of electricity needed in the 3DCP technique would significantly increase the generated CO_2-eq during construction. Finally, since the same post-tensioning technique is assumed in both bridges, the GWP

impact of the installation stage is almost the same in both scenarios. The slight differences are shown in Figure 5.b is due to the differences in the weight of the bridges as they need to be transported to and installed on the site. The precast bridge is heavier than the 3DCP bridge due to the higher amount of materials, resulting in a slightly higher generated CO_2-eq in the installation stage.



a. Total CO_2 Eq amount *b. CO_2 Eq ratio*

Figure 5. The GWP impact of each stage in bridge construction

Figure 6 shows comparative LCA results of the 3DCP and precast bridges in various environmental impact categories. As it is stated, the GWP impact of the 3DCP bridge is 80% of the precast bridge. As the results show, the 3DCP bridge reduced environmental effects regarding water consumption (due to removing the curing process) and ecotoxicity and acidification potentials (due to removing the need for reinforcement and formwork). On the other hand, the precast bridge performed better in the impact categories of land use and mineral resource scarcity compared to the 3DCP bridge, mainly due to the use of a smaller amount of cement in the concrete mixture.

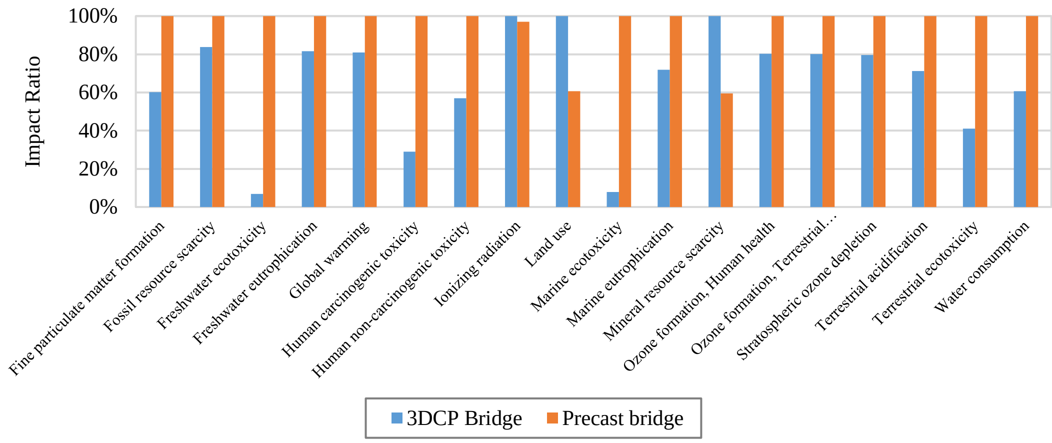


Figure 6. The comparative ratio of environmental impact assessment in bridge construction

Conclusion

This study compared the environmental impacts between precast and 3DCP techniques with a pedestrian bridge case study. The case study was a small concrete pedestrian bridge built in 2017 in the Netherlands using extrusion-based 3DCP with cement-based materials. Using the information of this bridge, a similar bridge was designed with a concentration on the cast-in-place post-tensioned concrete box girder technique. The designed precast bridge had the exact geometry as the C3DP bridge and was designed based on AASHTO standards. The cradle-to-site LCA results showed that cement was responsible for 85% of the generated CO2-eq regarding concrete used in the bridge. In addition, the concrete used in the 3DCP bridge had a higher GWP impact than the precast bridge due to a higher amount of cement in printable concretes. However, since C3DP used less material than the precast technique, there was no significant difference between the GWP impact of the concrete used in the whole bridge in both scenarios. In addition, due to the use of reinforcement and formwork in the precast technique, the GWP impact of the total materials used in the precast bridge was higher than the 3DCP bridge. Notably, due to using electricity for printing, the GWP impact of the construction process in 3DCP was also higher than the precast technique. Finally, the total generated CO_2-eq in the construction of the studied bridge using the 3DCP method was estimated to be 80% of the precast method.

Overall, the results of this study showed no significant difference on the environmental impact of constructing a small concrete bridge using 3DCP or precast methods. The significant difference between the two methods is during the construction, where 3D printers usually require a significant amount of electricity for printing concrete, resulting in four times more CO_2 generation. However, switching to other energy sources, such as renewables, can address this issue in the future. Furthermore, although the current printable concrete requires a higher amount of cement, resulting in higher environmental impact, 3DCP can significantly reduce the need for materials. By improving the printable concretes and replacing cement with environmental-friendly substitutes, the environmental impact of constructing infrastructure using 3DCP could be dramatically improved. Knowing that 3DCP allows for a great deal of geometric customization, reduces the construction time, requires minimum human labor, and is less expensive, the rapid advancements and significant investments in this technology indicate its great potential for automating bridge construction in the near future.

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References

AASHTO: The American Association of State Highway and Transportation Officials. 2022. Span CIPPTCBGB. In *Span Cast-in-Place Post-Tensioned Concrete Box Girder*.

Agustí-Juan, Isolda, and Guillaume Habert. 2017. "Environmental design guidelines for digital fabrication." *Journal of Cleaner Production* 142 (4).

Alhumayani, Hashem, Mohamed Gomaa, Veronica Soebarto, and Wassim Jabi. 2020. "Environmental assessment of large-scale 3D printing in construction: A comparative study between cob and concrete." *Journal of Cleaner Production* 270:122463.

Bos, F., R. Wolfs, Z. Ahmed, and T. Salet. 2016. "Additive manufacturing of concrete in construction: potentials and challenges of 3D concrete printing." *Virtual and Physical Prototyping* 11 (3).

Bos, P Freek, Y Zeeshan Ahmed, R Evgeniy Jutinov, and A. M. Theo Salet. 2017. "Experimental Exploration of Metal Cable as Reinforcement in 3D Printed Concrete." *Material* 10 (11).

Buswell, R. A., W. R. Leal de Silva, S. Z. Jones, and J. Dirrenberger. 2018. "3D printing using concrete extrusion: A roadmap for research." *Cement and Concrete Research* 112:37-49.

Davtalab, Omid, A. Kazemian, X. Yuan, and B. Khoshnevis. 2022. "Automated inspection in robotic additive manufacturing using deep learning for layer deformation detection." *Journal of Intelligent Manufacturing* 33 (3):771-784.

De Soto, B.G., I. Agusti-Juan, J. Hunhevicz, S. Joss, K. Graser, G. Habert, and B. Adey. 2018. "Productivity of digital fabrication in construction: Cost and time analysis of a robotically built wall." *Automation in Construction*, 92.

Faludi, J., C. Bayley, S. Bhogal, and M. Iribarne, 2015. "Comparing environmental impacts of additive manufacturing vs traditional machining via life-cycle assessment." *Rapid Prototyping Journal*, 21(1).

Fenner, A., C. Kibert, J. Woo, S. Morque, M. Rezkenari, H. Hakim, and X. Lu. 2018. "The carbon footprint of buildings: A review of methodologies and applications." *Renewable & Sustainable Energy Reviews*, 94.

Formoso C., L. Soibelman, C. De Cesare, and L. Isatto Eduardo. 2002. "Material Waste in Building Industry: Main Causes and Prevention." *Journal of Construction Engineering and Management* 128 (4).

GreenDelta. 2020. " Basic Modelling in openLCA." In *OpenLCA Tutorial*.

Hong, Jingke, Geoffrey Shen, Yong Feng, William Lau, and Chao Mao. 2015. "Greenhouse gas emissions during the construction phase of a building a case study in China." *Journal of Cleaner Production* 103 (2).

ISO: International Organization for Standardization. 2006. Environmental Management: Life Cycle Assessment; Principles and Framework. ISO: Geneva, Switzerland.

Kazaz, A., S. Ulubeyli, B. Er, V. Arslan, A. Arslan, and M. Atici. 2015. "Fresh Ready-mixed Concrete Waste in Construction Projects: A Planning Approach." *Procedia Engineering* 123

Khoshnevis, Behrokh. 2004. "Automated construction by contour crafting—related robotics and information technologies." Automation in Construction. 13 (1): 5–19.

Kuzmenko, Kateryna, Nicolas Ducoulombier, Adelaïde Feraille, and Nicolas Roussel. 2022. "Environmental impact of extrusion-based additive manufacturing: genericmodel, power measurements and influence of printing resolution." *Cement and Concrete Research* 157.

Liu , Siyu, B ing Lu, Hongliang Li , Zehua Pan , Jingjing Jiang , and Shunzhi Qian. 2022. "A comparative study on environmental performance of 3D printing and conventional casting of concrete products with industrial wastes." *Cement and Concrete Research* 298 (134310).

Lyu, Fuyan, Dongliang Zhao, Xiaohui Hou, Li Sun, and Qiang Zhang. 2021. Overview of the Development of 3D-Printing Concrete: A Review. *Applied Sciences* 11 (21).

Mechtcherine, Viktor, Jasmin Grafe, Venkatesh N. Nerella, Erik Spaniol, Martin Hertel, and Uwe Füssel. 2018. "3D-printed steel reinforcement for digital concrete construction – Manufacture, mechanical properties and bond behavior." *Construction and Building Materials* 179:125-137.

Miryousefi Ata, Sara, Ali Kazemian, and Amirhosein Jafari. 2021. "Application of Concrete 3D Printing for Bridge Construction: Current Challenges and Future Directions." *American Society of Civil Engineers Construction Research Congress (CRC)*.

Mohammad, Malek, Eyad Masad, and Sami G. Al-Ghamdi. 2020. 3D Concrete Printing Sustainability: A Comparative LCA of Four Construction Method Scenarios. *Buildings* 10 (12).

Salet, A. M, Theo, Zeeshan Ahmed Y, Freek Bos P, and Hans Laagland L. M. 2018. "Design of a 3D printed concrete bridge by testing." *Taylor and Francis* 13 (3).

Scrivener, K., V. John, and E. Gartner. 2018. "Eco-efficient cements: Potential economically viable solutions for a low-CO_2 cement-based materials industry" *Cement and Concrete Research* 114.

Tam, V., L. Shen, and C. Tam. 2007 "Assessing levels of material wastage affected by sub-contracting relationships and projects types with their correlations." *Building and Environment* 42 (3)

Tuan, D. Ngo, Kashani A lireza, Imbalzano Gabriele , T.Q. Nguyen Kate, and Hui David. 2018. "Additive manufacturing (3D printing): A review of materials, methods, applications and challenges." *Composites Part B: Engineering* 143.

Vantyghem, Gieljan, Wouter De Corte, Emad Shakour, and Oded Amir. 2020. 3D printing of a post-tensioned concrete girder designed by topology optimization. *Automation in Construction* 112.

Weng, Y., M. Li, S. Ruan, T. Wong, M. Tan, K. Yeong, and S. Qian. 2020. "Comparative economic, environmental and productivity assessment of a concrete bathroom unit fabricated through 3D printing and a precast approach." *Journal of Cleaner Production* 261.

Wolfs, R. J. M., and A. S. J. Suiker. 2019. "Structural failure during extrusion-based 3D printing processes." *The International Journal of Advanced Manufacturing Technology* 104 (1).

Xu, Weiguo, Yuan Gao, Chenwei Sun, Z. H. I. Wang, Jane Burry, Jenny Sabin, B. O. B. Sheil, and Marilena Skavara. 2020. "fabrication and application of 3d-printed concrete structural components in the Baoshan pedestrian bridge project." In *Fabricate 2020*, 140-147.

Yan, H., Q. Shen, L. Fan, Y. Wang, and L. Zhang. 2020. "Greenhouse gas emissions in building construction: A case study of One Peking in Hong Kong." *Building and Environment*, 45(4), April 2010, Pages 949-955.

Zeng, R. and A. Chini. 2017. "A review of research on embodied energy of buildings using bibliometric analysis." *Energy and Buildings*, Volume 155, 15 November 2017, Pages 172-184

Zhang, Jieru, Gengyuan Liu, Bin Chen, Dan Song, Jing Qi, and Xinyu Liu. 2014. "Analysis of CO_2 Emission for the Cement Manufacturing with Alternative Raw Materials: A LCA-based Framework." *Energy Procedia* 61:2541-2545.

Open-Resource Examination: Merits of an Alternate Approach to Student Assessment

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Traditional examination methods are not always sufficient for measuring a student's knowledge, skills, or abilities on a given subject. These traditional exams also create sufficient anxiety for the student to warrant the exploration of alternative assessment methods. Open-resource examination was explored in this longitudinal study that spans a six-year timeline in a construction finance course. The use of an online application to design, administer, and grade was considered in this study. This was accompanied with a survey of the students. Exam results as well as survey results are presented and discussed in this paper. Descriptive statistics were used to evaluate the results over the timeline of the study. Advantages to students include reduced exam anxiety, immediate results, and control of exam location and environment. Advantages to instructors include automated grading as well as statistical analysis of individual exam questions and aggregate performance. Additionally, both instructor and student gain valuable class-time to treat content and context of the subject. Limitations of open-resources exams are also considered. The results make a compelling case for a broader implementation of open-resource, online exams.

Key Words: Assessment Methods, Construction Education, Open-resource Exams

Introduction

The career pathway of a construction manager is highly technical, demands organizational skills, and the ability to command a vast library of resources. With repetition and experience, the construction manager commits certain aspects of the job to memory. Regardless of their knowledge and intelligence, many construction managers are highly adept at *organizing* access to information rather than storing that information in their active memory. They are expert in process management and interpreting information into insight for decision making. Construction managers are not the *creators* of new knowledge – but they are the highly effective *users* of knowledge. Thus, construction management education considers creative ways to teach interpretation, critical thinking, and pragmatic application skills. It is therefore necessary that assessment methods in construction management education reflect that teaching approach.

The purpose of this paper is to provide insight into the potential use of open-resource examination in construction education. The merits as well as the challenges are presented, and the results of five years of use are considered herein. The open-resource examination was used in one course of that time period, and as such, general application to all courses in a construction management (CM) program are not considered. The approach is explored herein and presented for consideration by a broader audience. Therefore, this paper serves to inform that broader audience of CM educators.

Background and Literature Review

Educational assessment techniques are critical to student engagement and motivation beyond measurement purposes. The traditional assessment techniques typically provide the effectiveness of the learning and teaching processes and focus less on revealing the long-term retention of knowledge. Several studies focused on analyzing the relationships between assessment techniques, learning theory, individual achievements, evaluating programs, and mental processing (Brookhart, 2003; Dwyer, 2006; Taras, 2010; Andrade, 2013; Safapour et al. 2019; Kang et al. 2021).

National Research Council (NRC)'s study in 2001 explored the issues in traditional assessment techniques such as (i) the use of a single type assessment in all topics and/or programs, (ii) the lack of design and connection of assessments on cognition, observation, and interpretation, (iii) absence of an approach considering cognitive science and learning representing students' competencies and (iv) insufficient structure of innovative and authentic teaching approaches in the practical applications (NRC, 2001). As suggested in general assessment theory, standardized assessment procedures are often useful in measuring knowledge at a specific point in time (Rovai, 2000); however, they are ineffective in assessing the overall learning performance.

Opportunities of Open-Resource Examinations

Open-resource examination techniques received increasing attention in the educational assessment literature as an alternative and authentic assessment method. For example, Green et al. (2019) focused on using open-resource exams to enhance student learning, performance, and motivation. Their study revealed that students could focus on mastering materials rather than memorization and short-term learning, such as applying equations without a fundamental understanding of principles. In addition, statistical significance was identified in the effectiveness of open-resource exams in the same study. The same study also emphasized the importance of exam protocol to prevent students from solely transferring information from the textbook rather than utilizing the textbook information in testing critical thinking and applying concepts (Green et al., 2019).

Chappius and Stiggins (2002) identified that open-resource examination approach can be considered as an assessment that supports student learning with increasing motivation and engagement. As indicated in the very early studies (Feldhusen, 1961), students reported their positive experiences in open resource examinations such as reduced anxiety, lower tendency to cheat, and promoted learning during the exam even though they didn't have a structured exam protocol. In addition, current literature highlighting the effectiveness of open resource examinations reported that students appreciate the time and location flexibility of the exams and the focus on mastering content with applying relevant skills (Williams & Wong, 2009).

Challenges of Open-Resource Examinations

On the other hand, studies indicated that open-resource examination style may lead to decrease class attendance (Moore & Jensen, 2007) and may devote less effort to studying (Parker et al., 2021). In addition, overconfidence is a critical problem in open-resource examinations, which may lead to inadequate preparation for the exam (Theophilides et al., 2000). Another potential issue in the literature highlighted is the time spent finding the information in the resources while taking the exam (Theophilides et al., 2000). Students might also have challenges with overall time management in the open-resource examinations, spending more time finding answers to certain questions, which then results in not having enough time for some questions (Cahill-Ripley, 2015). The structure of questions and the time limit have a significant impact on the student's performance in the open-resource examinations. Deneen (2020) provided a guideline for the open-resource examinations by emphasizing the structure of the exams with a focus on using and applying the knowledge rather than investigating additional and new knowledge. Their study suggests structuring the open-resource examinations by asking problem-solving, analysis, data-interpretation, and compare & contrast type of questions (Deneen, 2020).

Considering these, instructors have a critical role in conveying the objectives of the open-resource examination with clear exam protocol to students. Understanding the fundamental purpose of this type of exam will increase student's engagement in terms of attendance, attention to course material, and their study efforts. Moreover, the instructors must comprehensively assess the pros and cons of the open-resource examinations with the subject matter and question types.

Other considerations in the learning assessments

Test anxiety is a prominent problem that negatively influences students' performance. Cassady and Johnson (2001) revealed that a higher level of cognitive test anxiety is associated with significantly lower test scores. In addition, Chapell et al. (2005) 's study focusing on the relationship between test anxiety and test performance identified that female undergraduate and graduate students have higher test anxiety levels. The various causes of text anxiety were explored in the literature extensively. For example, Mealey and Host (1992) identified three categories that lead to text anxiety: (i) lack of study and preparation strategies, (ii) distraction at the time of the exam, and (iii) misconception of adequate study and preparation strategies. Moreover, examination type (essay, multiple choice, open-ended, etc.), time limit, length, lack of clarity in instructions, environment, and stress of final score were identified as contributing factors to test anxiety (Young 1999; Van Blerkom, 2008; Trifoni & Shahini, 2011). Subsequently, instructors should provide the logistics of the examination, such as length, and type of questions, with a practice exam, which increases students' awareness of the exam style and supports them on feeling familiar and comfortable with reduced test anxiety.

As an effective alternative to traditional teaching and learning techniques, student-to-student learning provided promising results in the recent studies. Student-to-student learning approach transitions the individual learning process to a team and group based active learning style (MacLeod et al., 2018). Allen (2000) identified that it improves peer communications and supports students in being more open and transparent to each other. Considering the importance of interpersonal skills in almost every profession, student-to-student learning approach empowers development of these skills: communication, active listening, teamwork, patience, motivation, etc. Rugut and Chemosit (2009) focused on determining relationships between motivation and student-to-student learning. Their study revealed that student-to-student relations is a statistically significant predictor of the student motivation (Rugut & Chemosit, 2009). Ultimately, it is evident that alternative and authentic assessment and teaching techniques lead to improve student's performance with promoting their learning experience with an active style.

Theoretical Background of Assessments

It seems apparent that a deviation from traditional assessment methods is appropriate – and perhaps more so with construction management students. Considering the notable benefits of open-resources examination, namely reduced anxiety, lower tendency to cheat, and promoted learning during the exam; we considered the development of an open-resource examination in the construction finance course offered within the Construction Management program at Colorado State University. In addition to these three benefits, we sought to also increase the rigor of the exam without negatively impacting performance (average grade).

Research Methodology

Exam Development and Administration

Addressing exam anxiety presents an interesting challenge, as anxiety types vary from student to student (Moisiu, 2011). To remove, or at least attempt to diminish some of these exam anxieties – an online examination was designed. The online exam was created to allow the student to choose their test location – thus addressing the concern for environmental conditions. Many distractions may exist during scheduled exams in specified spaces. Thus, the freedom to choose the exam location provides options for the student to determine the best location for their particular preferences.

One of the distractors is time limits (Young, 1998). Often, a traditional exam is administered in the scheduled classroom setting and has a limit to the time allotted for the course. Therefore, this exam was designed to allow the student a window of time over the course of three days. This allowed the student to work on the exam at their pace. And, as distractors or other scheduled events interrupted the student – the online application automatically saved their work. After three days (72 hours) the exam was shut off for all students.

Some exam anxiety is the result of under preparation by the student. They "mistakenly believe they have adequate" preparation (Mealey & Host, 1992) but as soon they begin the exam, they realize they have not prepared sufficiently. Thus, this open-resource examination allowed the student to accompany the exam administration time with their preparation time. Where traditional examinations require sufficient time to study or "cram" information related to the exam – this exam allowed students to identify the problem, study the appropriate strategy to solve the problem (or question), and to determine their response. This exam writing strategy also justified the necessary extension to the time limit. Prior to the administration of the exam, students were informed of this condition and cautioned that if the student chose to use this strategy to study-as-you-go, that the full time to take the exam would be significantly extended.

In open-resource exams, there immediately exists the concern for cheating. To address this concern, the exam was written with both (i) pools of questions and (ii) variable questions. Questions pools are used so that multiple choice, true/false, fill-in-the-blank questions can be written on the same, or similar question but the same level of rigor. The online application automates a random choice for which question is presented to the student. Thus, with a sufficient pool of questions the likelihood of the same question presented to two or more students collaborating together is very low. Another strategy within the pool is to have questions rephrased. As a simple example, the following are questions from the same pool:

1. True or False: A project with a negative NPV has not met a company's minimal attractive rate of return. (Answer: True)
2. True or False: A project with a positive NPV has not met a company's minimal attractive rate of return. (Answer: False)
3. True or False: A project with a negative NPV is an indication that the IRR is greater than the MARR. (Answer: False)
4. True or False: A project with a positive NPV is an indication that the IRR is greater than the MARR. (Answer: True)

These four questions would be one of ten or twelve which the exam application can select for each student. Note, the rigor of these questions are relatively the same. Questions with higher standards on the Bloom's taxonomy were associated in the same pools – considering the fairness of the test from student to student without diminishing the rigor.

Further variability in the question pool was achieved by using problem variables within the question. A simple example of this was a question pool which asked the student to calculate either the Schedule Performance Index (SPI) or the Cost Performance Index (CPI) given three variables: Budgeted Cost of Work Scheduled (BCWS), Budgeted Cost of Work Performed (BCWP), and Actual Cost of Work Performed (ACWP). On the programming side of the exam application, the instructor was able to create a range of values for each of these three variables, then program the simple logarithm to achieve the answer. Thus, the question can produce innumerable potential answers – but the student will only have one correct answer.

Other examples of this would be to present the student with a summary balance sheet or income statement, with each value varied by the computer application. Next, the instructor programmed which financial ratio to calculate. This singular question becomes 50 questions and yet challenged the students at the same level of rigor.

While this exam writing approach was designed to eliminate cheating (because students simply were not taking an exam with the same questions), it was designed to promote student-to-student teaching and learning. Students were cautioned regarding the structure of the exam, and to not rely solely on the appearance of the question being the same, as some questions may seem the same but in fact the rephrasing of questions may have changed. However, students were not discouraged from using each other as knowledge resources. Peer-to-peer teaching can be a powerful tool, both for the student-learner (the student who is learning from another student) and for the student-teacher (the student who is also enrolled in the course but takes on the role of providing knowledge to the fellow student). In many cases, student-learners may have difficulty applying the instruction and context provided by the instructor/professor. A second voice, which explains the same material but in a different manner, may have a significant impact on the student-learner's ability to retain and now apply the new knowledge. Or, as often may be the case, the student-learner has merely forgotten the lesson taught – even though there was a level of confidence at the time that the principle was introduced. Additionally, the student-teacher gains from the experience of providing explanation to a fellow student. This process serves to reinforce their own learning. Indeed, this process or interaction was suggested from the instructor with a word of caution regarding the use of student-teacher provided information. Ultimately, the student-learner was responsible for their own final response and could not hold the student-teacher accountable for the exchange of knowledge.

In the development of the open-resource exam, there was a going concern for the rigor. There still remained a number of questions which assessed the student at the foundational 'Understanding' level on the Bloom's taxonomy – but there was now an opportunity to increase the rigor and challenge the students at higher levels of knowledge, skills, and abilities related to the course content. The open-resource exam format also presented an opportunity to more fully examine the students' knowledge, skills, and abilities on a more comprehensive level. Thus, the length of time for the exam could be extended sufficiently to meet those expectations.

Initially in 2018, only the mid-term exam was administered through this online application and the final exam was administered in a traditional two-hour, in-class format. After some initial success, the final exam was in development when the COVID-19 pandemic impacted educational institutions around the world. This condition forced the final development and completion of the final exam in an online format. To ensure consistency in the results of this study, only the mid-term exam was considered for its effectiveness over the five-year period.

Development of a Feedback Instrument

A survey instrument was developed in 2019 to consider the impact of the students' experience with the open-resource examination. The survey was purposefully brief, with only 14 questions, to increase the response rate. The survey was administered through the same online application as the exam. Extra-credit points were awarded to students for participating – incentivizing participation. Twelve questions used a Likert-type scale from 'Strongly Agree' to 'Strongly Disagree'. One question asked the students regarding the time necessary to take the exam and used a Likert-type scale from, "Took a lot more time than normal" to "Took much less time than normal". One question was a simple, Yes or No response. Table 1 provides the list of questions and the response type.

Table 1

Survey Questions and Question Types

Question No.	Survey Question	Response Type
1.	The open-resource mid-term was a good measure of my understanding of the material	Likert-Type
2.	The open-resource format provided sufficient time to complete the mid-term	Likert-Type
3.	I was able to collaborate with others while taking some or all of the exam	Yes or No
4.	The ability to collaborate on the exam created an opportunity for me to learn from others also taking the exam.	Likert-Type
5.	The ability to collaborate on the mid-term created an opportunity to help others learn from me.	Likert-Type
6.	The open-resource mid-term encourages students to take advantage of other students' knowledge and learning without making the effort to learn themselves.	Likert-Type
7.	The collaborative nature of the mid-term helped reinforce my learning because I was able to confirm my answers with others working the same, or similar problems.	Likert-Type
8.	I spent sufficient time studying and preparing prior to taking the exam.	Likert-Type

9.	Considering the time it takes to study for AND take the exam, this mid-term…	Likert-Type
10.	I prefer the open-resource mid-term	Likert-Type
11.	Traditional examinations are NOT effective at measuring my knowledge, skills, or abilities (Traditional examinations are in-class, closed resource exams).	Likert-Type
12.	I prefer in-class, open note examinations over the open-resource examination used on this mid-term.	Likert-Type
13.	Examinations are an effective way to measure a student's learning and intelligence on a given subject.	Likert-Type
14.	This open-resource mid-term challenges me to learn the material.	Likert-Type

The survey was administered after each mid-term examination and open for a full week. The extra-credit points associated with participation were awarded separately from the exam scores reported in the results section of this paper. The survey followed IRB protocols and indicated that participation was voluntary and that the aggregate results could be used in further research and publication.

Results

Prior to the use of the open-resource exam, the average mid-term exam score was 88.7% and 83% in the spring and fall of 2017, respectively. In the spring of 2018, the open resource exam was used for the first time. We observed that the average exam score initially dropped and then leveled out again in the mid 80's. The exam analytics in the online application provided average scores on each question as well as the standard deviation – thus assisting the instructor in identifying those exam questions which caused the most problems, or challenges for the students. This also served to consider whether the question was written appropriately. In each semester, there were small iterations for improving the exam, adding content or rigor and revising or removing poorly written questions.

Table 2 provides the average score in percent form, as well as the low and high scores, and student enrollment count in a given semester.

Table 2

Descriptive Statistic Metric of Mid-Term Exam Results

Year of Exam	**Average % Score**	**Low Score**	**High Score**	**Student Count**
Spring 2017	88.7%	69%	98.5%	20
Fall 2017	83.9%	45%	96%	28
Spring 2018	79%	66%	94%	57
Spring 2019	87.5%	69%	98%	76
Spring 2020	85%	69%	97%	89
Spring 2021	81.2%	0% (58%)	98.7%	75
Spring 2022	86.4%	64%	100%	86

Participation rates for the survey varied somewhat, yet the responses were relatively consistent from year-to-year. The first semester wherein the survey was administered was the Spring of 2019. The total participation in the survey was 67 out of 74 students enrolled in the course, a response rate of 90.5%. In the Spring of 2020, we observed 65 responses out of 89 students enrolled in the course, a response rate of 73.0%. In the Spring of 2021, we observed 62 responses out of 74 students enrolled in the course, a response rate of 83.8%. Finally, in the Spring of 2022, we observed 80 responses out of 86 students enrolled in the course, a response rate of 93%.

With an overall participation of 274 students out of a potential 323 students enrolled, the four year participation rate was 84.8%. Participation was incentivized with 2 points of extra credit, which was applied to the total grade score for the course (not the exam – so to not skew the results).

Table 3

Results from Student Survey over 4-years

Question No.	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree	No Response
1.	**138 (50.4%)**	121 (44.2%)	13 (4.7%)	2 (0.7%)	0	0
2.	**209 (76.3%)**	60 (21.9%)	3 (1.1%)	2 (0.7%)	0	0
3.	**[YES] 211 (77%)**	[NO] 63 (23.0%)				
4.	**144 (52.6%)**	76 (27.7%)	41 (15.0%)	8 (2.9%)	4 (1.5%)	1 (0.4%)
5.	**123 (44.9%)**	94 (34.3%)	45 (16.4%	7 (2.6%)	4 (1.5%)	1 (0.4%)
6.	41 (15.0%)	42 (15.2%)	64 (23.4%)	**87 (31.8%)**	39 (14.2%)	1 (0.4%)
7.	**118 (43.1%)**	104 (38.0%)	41 (15.0%)	8 (2.9%)	1 (0.4%)	2 (0.7%)
8.	81 (29.6%)	**134 (48.9%)**	45 (16.4%)	14 (5.1%)	0	0
9.	[A Lot more] 36 (13.1%)	**[A little more] 132 (48.2%)**	[the same] 87 (31.8%)	[A little less] 15 (5.5%)	[Much less] 3 (1.1%)	0
10.	**225 (82.1%)**	44 (16.1%)	5 (1.8%)	0	0	0
11.	**101 (36.9%)**	92 (33.6%)	59 (21.5%)	18 (6.6%)	4 (1.5%)	0
12.	19 (6.9%)	12 (4.4%)	42 (15.3%)	**126 (46.0%)**	75 (27.4%)	0
13.	23 (8.4%)	**95 (34.7%)**	90 (32.8%)	54 (19.7%)	12 (4.4%)	0
14.	96 (35.0%)	**152 (55.5%)**	23 (8.4%)	3 (1.1%)	0	0

Discussion of Results

For nearly every one of the fourteen survey questions, the students expressed an overall preference for the open-resource examination structure. Students felt it was a good measure of their understanding of the course material (94.6%) – yet the same could be said of most, well-written exams. 98% of students agreed that there was sufficient time to complete the exam – addressing one of the most common causes of exam anxiety. 77% of students took advantage of the opportunity to work in a collaborative environment and about 80% expressed that this environment created both an opportunity to help others and to be helped by fellow students. This finding may be the strongest, and most meaningful reason for administering an open-resource exam. There were differing opinions about whether the format encourages taking advantage of other students' learning. However, 46% disagreed with that fact. It should be noted, that over the four years of the survey, there was a declining trend in the number of students who agreed with this statement. This may be a result of the increased variability and rigor of the exam writing. In a related question though, 81.1% of students indicated that they leveraged the format to verify their own results.

Most students (78.5%) reported that they did spend sufficient time studying and preparing prior to taking the exam. The following questioned asked the students to compare the time it took to take the exam compared to a traditional exam. Only 6.6% students indicated that it took less time than normal, while 31.8% indicated that it was about the same amount of time. One of the objectives of creating the open resource exam was to increase the rigor – and the anticipated byproduct was a longer exam. Therefore, when 61.3% of students indicated that it took a little more, or a lot more time – those results were not surprising.

The last five questions inquired about exam-format preferences. An overwhelming 82.1% 'Strongly Agreed' to their preference for open-resources exams, accompanied by another 16.1% who Agreed. There were no disagreements. However, a similar question was asked in the same manner, "I prefer in-class, open note exams OVER the open-resource exam." In this case, there were 11.3% of students changed their answer. This may be the result of shifting the question from a positive to a negative to validate the original question. Regardless, there were still 73.4% who disagreed and still indicated the preference for open-resource exams. Another question was asked with a negative connotation instead of a positive one, "Traditional exams are NOT effective…" – to which students responded with a 70.5% disagreement. Another similar, but different question was asked in a positive way, "examinations are an effective way to measure a student's learning and intelligence on a given subject". The responses to this question were the most varied in distribution, with only 34.7% of students agreeing, and 32.8% at a neutral position. This speaks highly of the need to consider alternative methods of assessment. Finally, the question was asked whether the open-resource exam challenged the students to learn the material, to which 90.5% indicated their agreement. Only 3 students disagreed and none strongly disagreed.

A number of advantages became apparent after moving to an online application to administer the exam. First, the students received their grades immediately after submitting their exam. Specific analysis of which questions are correct or incorrect are not available until after the exam window is closed, however the total score is calculated and provided to the student. This feature can relieve anxiety for the student – and those that performed lower than anticipated were able to schedule time with the instructor to review those questions missed or misunderstood.

Similarly, with the immediate analytics, the instructor was able to focus the exam review on the questions which were more frequently missed – or where increased instruction was needed. During the post-review of the exam, the instructor displayed the descriptive statistical results of the exam as well as the low and high scores, the standard deviation, and most frequently missed questions. This feedback became helpful to students who were concerned about their ranking in the class, or their performance relative to other students. Most importantly, students were able to ask specific questions so that they could improve their performance for the subsequent final exam.

Additional benefits for the students included, better use of class instruction time, schedule flexibility for the students to take the exam, and the promotion of student-to-student learning. With shifting the exam time to out-of-class, the instructor gained a full lecture – allowing greater review of the material, more meaningful contextualization, and even additional content. Typically, the additional time was spent providing new examples for the same principles – thus allowing the students to consider the question conditions in a new light, or from a different perspective. It also allowed those students additional time to form and ask specific questions. With a greater window of time for the exam, the scheduling of the exam fell on the student according to their preferences.

One unforeseen benefit that was discovered after several iterations of the open-resource exam was that students were able to prove their own interpretation of tools, notes, and applications. Much of the in-class instruction for this course was accompanied with the use of spreadsheet software. Within the lecture time, students were challenged to create their own spreadsheets, program calculations, and determine results of increasingly complex problems. Because of this complexity, some students fall behind and get frustrated with needing to both learn the course material and develop the use of the spreadsheet tool. The collaborative nature of the open-resource exam allows students to verify their results with their peers. This peer-to-peer verification helps timid students who are not comfortable speaking up in a large classroom but do well with small-group work. One student described their experience while taking the exam. The student would perform their problem, while their peer did the same. Once the problem was solved, each other would solve their peer's problems using their own spreadsheet. If the same answer was achieved, they would validate their own spreadsheet. If the result of the question varied, then a follow-up discussion would ensue to determine where the error was made. Thus, the exam became a teaching and learning tool as well as an assessment tool.

Limitations

While examining the results of the mid-term from year to year, an initial decline was observed. However, this seemed to be more closely related to the development of the exam questions rather than the students' performance. With each semester, there was a necessary review of the validity of exam questions. The statistics included in the online application facilitated an evaluation of each question in the test and thus a re-write or removal of poorly written questions. There was also observed in the Spring of 2020 a decline in the exam results. This may have been a result of the Covid-19 induced environment in education. All students were entirely online during this semester, and observed participation and engagement were low. One student opened the exam but did not complete the exam, and the score of 0% was recorded. This score certainly lowered the class average in this semester. In this same semester, a score of 98.7% was earned on the same exam.

This study used an online survey instrument, and as such is limited to the students enrolled in the class and further limited to the students who chose to participate. With a response rate of 84.8% to the survey, the research must acknowledge the 15.2% of students who did not participate and could have held differing opinions from the results – and thus influenced the results had they participated. Another limitation is the application of the open-resource examination. In this study, the exam was used in a construction finance course – which lends itself to the ability to create such an examination with sufficient variability in the questions. Those considering an open-resource examination should carefully deliberate the appropriateness of this style of exam with the subject matter of the course. The authors make no statistical claim that this style of examination is better, same, or worse than other options – only that it was effective in this setting over the four-year period studied.

Conclusions

The open-resource examination was explored over a 5-year period, and the students in the most recent 4-year period were surveyed regarding their experience with the exam format. Some very positive results were found throughout the process of designing, administrating, and evaluating the value of this alternative assessment method. This exam format presents a number of advantages for both the student and the instructor – many of which have been discussed. With the increasing number of documented students with disabilities related to exam anxiety – the open-resource examination provides a valuable pressure release for the student. For those students with undocumented exam anxiety – this approach allows the instructor to facilitate a fair and inclusive learning environment.

The refinement of the exam in each iteration increases the rigor and variability of the exam. There still exists an opportunity for students to take advantage of other students' knowledge and learning without needing to make an effort for themselves to learn the content. Thus, the exam must continue to be improved. At the same time, many of those students who do not perform well in traditional classroom-lecture settings found that they gained sufficient knowledge and understanding of the material *during* the examination. This fact in itself may warrant the use of this assessment approach. Regardless, the conclusion of this study is that there are sufficient benefits for the student and the instructor to justify continued use and improvement of the open-resource exam method.

References

Allen, T. (2000). Creating community in your classroom. *Education Digest*, 65, 23–25.

Andrade, H. L. (2013). Classroom assessment in the context of learning theory and research. *SAGE handbook of research on classroom assessment*, 17-34.

Brookhart, S. M. (2003). Developing measurement theory for classroom assessment purposes and uses. *Educational measurement: Issues and practice*, 22(4), 5-12.

Amanda Cahill-Ripley (2015). Innovative methods of assessment in law: the value of open-book exams as a catalyst for improving teaching and learning in the law school. *The Law Teacher,* 49:2, 206-218.

Cassady, J. C., & Johnson, R. E. (2002). Cognitive test anxiety and academic performance. *Contemporary educational psychology*, 27(2), 270-295.

Chappuis, S., & Stiggins, R. J. (2002). Classroom assessment for learning. *Educational leadership*, 60(1), 40-44.

Deneen, C. (2020). *Assessment considerations in moving from closed-book to open-book exams. Teaching and Learning Short Guides*. Retrieved from December, 15, 2022, from https://melbourne-cshe.unimelb.edu.au/__data/assets/pdf_file/0010/3341944/closed-book-to-open-book-exam_final.pdf

Dwyer, C. A. (1998). Assessment and classroom learning: Theory and practice. *Assessment in Education: Principles, policy & practice*, 5(1), 131-137.

Feldhusen, J. F. (1961). An evaluation of college students' reactions to open book examinations. *Educational and Psychological Measurement*, 21(3), 637-646.

Green, S. G., Ferrante, C. J., & Heppard, K. A. (2016). Using Open-Book Exams to Enhance Student Learning, Performance, and Motivation. *Journal of Effective Teaching*, 16(1), 19-35.

Kang, H., & Furtak, E. M. (2021). Learning theory, classroom assessment, and equity. *Educational Measurement: Issues and Practice*, 40(3), 73-82.

MacLeod, J., Yang, H. H., Zhu, S., & Shi, Y. (2018). Technological factors and student-to-student connected classroom climate in cloud classrooms. *Journal of Educational Computing Research*, 56(6), 826–847. https ://doi.org/10.1177/07356 33117 73399 9.

Mealey, D. L., & Host, T. R. (1992). Coping with test anxiety. *College Teaching*, 40(4), 147-150.

Moore, R., & Jensen, P. A. (2007). Do open-book exams impede long-term learning in introductory biology courses?. *Journal of College Science Teaching*, 36(7), 46.

National Research Council. (2001). *Knowing What Students Know: The Science and Design of Educational Assessment*. Washington, DC: The National Academies Press. https://doi.org/10.17226/10019.

Parker, A. M., Watson, E., Dyck, N., & Carey, J. P. (2021). Traditional versus open-book exams in remote course delivery: a narrative review of the literature. *Proceedings of the Canadian Engineering Education Association (CEEA)*.

Rovai, A. P. (2000). Online and traditional assessments: what is the difference?. *The Internet and higher education*, 3(3), 141-151.

Rugutt, J., & Chemosit, C. C. (2009). What motivates students to learn? Contribution of student-to-student relations, student-faculty interaction and critical thinking skills. *Educational Research Quarterly*, 32(3), 16.

Safapour, E., Kermanshachi, S., & Taneja, P. (2019). A review of nontraditional teaching methods: Flipped classroom, gamification, case study, self-learning, and social media. *Education Sciences,* 9(4), 273.

Taras, M. (2007). Assessment for learning: Understanding theory to improve practice. *Journal of Further and higher education*, 31(4), 363-371.

Theophilides, C. & Koutselini, M. (2000). Study Behavior in the Closed-Book and the Open-Book Examination: A Comparative Analysis. *Educational Research and Evaluation: An International Journal on Theory and Practice,* 379–393, at p. 379.

Trifoni, A., & Shahini, M. (2011). How does exam anxiety affect the performance of university students?. *Mediterranean journal of social sciences,* 2(2), 93-93.

Van Blerkom, M. (2008). *Measurement and statistics for teachers*. Routledge.

Williams, J. B., & Wong, A. (2009). The efficacy of final examinations: A comparative study of closed-book, invigilated exams and open-book, open-web exams. *British Journal of Educational Technology*, *40*(2), 227-236.

Young, D. J. (1999). Affect in foreign language and second language learning. Boston, MA: McGraw-Hill.

Where Do Minority Serving Institutions Stand in the U.S. Construction Education? – Exploring ASC and ACCE Communities

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The construction industry is facing workforce shortages and a low retention rate for new professionals. Embracing diversity has been identified as a critical factor that can remediate this situation. Minority Serving Institutions (MSIs) are recognized as an important source to increase the diversity of minority representation to foster a next generation of diverse professionals. However, construction lacks an understanding of what MSIs actively take part of the current educational community across the U.S. This study investigates MSIs within the context of construction disciplines in the U.S. as an important part of the construction educational community. An exploratory analysis of the existing databases that contain MSI denominated institutions under the listings by the U.S. Department of Education was performed to identify the proportions of MSIs that offer construction programs, the types of programs being offered, the degree levels of the educational programs, and the participation of MSI within the Associated Schools of Construction (ASC) and the American Council for Construction Education (ACCE) academic communities. Based on the results from the MSI exploration in construction, a discussion is provided to stress the importance of connecting with these educational institutions to increase the number of new, diverse professionals into construction careers.

Key Words: Education, Construction, Minority, Diversity, Workforce Development

Introduction

Demand for construction professionals at all levels (i.e., skilled labor, managers, engineers) continue to increase in the U.S. every year. The U.S. Bureau of Labor Statistic reports that construction occupations are expected to grow between 4% to 8% from 2021 to 2031, with over 700,000 jobs projected to come from new and replacement positions (BLS, 2022-a; BLS, 2022-b). Importantly, the U.S. construction industry highlights issues with replacing an aging workforce. Older professionals leaving the industry once they reach retirement age are often not replaced due to a low influx of new incoming professionals (Suryadi, 2018). Workforce replacement issues have generated labor shortages and disruptions for the construction industry as a whole (Topping, 2018). Furthermore, the construction industry has unique challenges that reduce the likelihood of new professionals considering it as a career of choice. Some studies report that construction is negatively perceived by youth's parents (e.g., physically demanding, limited career progression, unsafe), with over 70% of parents indicating that they would not advise their children to pursue a construction career (NCCER, 2020). Other studies indicate that students simply do not get sufficient exposure to the construction industry in terms of career exploration, work experiences, or field trips (Bigelow et al., 2018). More recently, there has been an on-going discussion in academia regarding the lack of representation of minorities in construction (Cho et al., 2022). In the largely White, male-dominated construction domain, race and gender have been identified as critical factors that directly affect the influx of new professionals into the discipline (e.g., student retention rates, graduations) (Al-Bayati et al., 2017; Manesh et al., 2020). Diversity challenges to engage, attract, and retain new, diverse professionals to the workforce are not unique to construction. There is well documented literature in science, technology, engineering, and math (STEM) that shows similar diversity challenges to those experienced in construction (Fry et al., 2021). Race underrepresentation, gender imbalances, and wage gaps are some of the problems that are continually faced by minorities in STEM (Fry et al., 2021). Complex solutions that tackle these multidimensional problems of diversity in STEM education and workforce are still under continuous research. One approach that has been emphasized as a potential solution by the National Academies of Sciences, Engineering, and Medicine (NASEM), is the bolstering of Minority Serving Institutions across the U.S. (NASEM, 2019). These types of educational institutions are of interest to solve the diversity issue in STEM because they provide a clear pathway to educational success and workforce readiness centered on minority communities (NASEM, 2019).

Although Minority Serving Institutions (MSIs) are recognized as an important source to increase diversity of minority representation within the STEM workforce, these educational institutions have not been studied in the context of construction. Currently, there is a gap in understanding what Minority Serving Institutions actively form part of the construction educational community to foster and guide the next generation of diverse professionals towards the workforce. This study focuses on exploring who are MSIs in the U.S. that provide construction educational programs, what types of degrees are offered, and what is their relationship with established educational communities in construction (i.e., the Associated Schools of Construction (ASC) and the American Council for Construction Education (ACCE). This paper contributes to the on-going discussion in academia regarding diversity, equity, and inclusion by identifying what MSIs are currently within the U.S. educational community of construction. Moreover, this paper highlights the need to engage and connect with the existing MSIs across the U.S., as these educational institutions offer opportunities to increase recruitment and retention of much needed new professionals into construction careers.

Background

What is the State of Gender and Racial Diversity in the U.S. Construction Industry and Education?

The current trends in industry employment show a lack of minority participation in the construction domain. The U.S. Bureau of Labor Statistics data highlights a large imbalance among the total employed persons in construction in terms of race and gender. White Americans represent a large proportion of the construction industry, composing 87.9% of the construction workforce (BLS, 2022-

c). Female professionals compose a very small percentage of the workforce with 11% of all people in the industry (BLS, 2022-c). Racial minorities also represent smaller portions of the workforce, with Hispanics (32.6%) presenting higher participation when compared to African Americans (6.3%) and Asian Americans (2.1%) (BLS, 2022-c). Participation of Native Americans, Pacific Islanders, Alaska Natives, and Native Hawaiians appears to be so reduced that data is not shown for labor workforce within the construction industry (BLS, 2022-c). These participation patterns of minorities in construction can be observed across multiple employment levels, including skilled labor (BLS, 2022-a), construction managers (BLS, 2022-b), and architecture and engineering positions (BLS, 2022-d).

Similar participation patterns in terms of diversity can be found in the U.S. construction education. The number of degrees awarded within higher education institutions (2-year or 4-year institutions) for students in construction are still largely obtained by White American students (55.3%) (DataUSA, 2022). Gender imbalances are also a prevalent problem, with a very small proportion of construction degrees obtained by female students (DataUSA, 2022). Similarly, racial minorities have a smaller number of degrees awarded at U.S. educational institutions. Mirroring the construction industry participation, Hispanics (21.9%) represent a larger proportion of the degrees awarded in construction when compared with African Americans (11.3%%), Asian Americans (2.42%), Alaska Natives (1.44%), and Native Hawaiian and Pacific Islanders (0.39%) (DataUSA, 2022). These patterns in higher education can also be found within labor trade educational programs. The latest reports by the U.S. Department of Labor (2021) highlight a lack of participation and graduation of minorities in apprenticeship programs. White American apprentices who completed their apprenticeship training in 2021 accounted for 42% of all trade graduates. On the other hand, Females (16%), Hispanics (18%), African Americans (6%), Asian Americans (1.5%), Pacific Islander Americans (0.7%), and Native Americans (1%) achieved much lower completion rates (U.S. Department of Labor, 2021).

What are Minority Serving Institutions (MSIs)?

The U.S. Department of Education defines Minority Serving Institutions (MSIs) as institutions of higher education (2-year or 4-year institutions) whose enrolling populations of minority students exceeds a given percent of the total student enrollment (U.S. Department of Education, 2011). These programs are explicitly supported by grant programs that can be obtained through the U.S. government to advance their goals and aims, while supporting equity, excellence, and economic opportunity within their communities. MSIs are grouped into seven minority student-serving categories as described below. It is important to highlight that higher education institutions under these categories are not monolithic and can have intersectionality of identities and communities across multiple of these groupings (i.e., institutions can have multiple MSI denominations).

- *Historically Black Colleges and Universities (HBCUs):* Colleges or universities established prior to 1964, whose principal mission was, and is, the education of Black Americans. The colleges or universities are accredited by a nationally recognized accrediting agency or association (National Center of Education Statistics, 2020).
- *Hispanic Serving Institutions (HSIs):* Higher education institutions that aim to improve the academic attainment of Hispanic students. These intuitions must have an enrollment of undergraduate full-time students that is at least twenty-five percent Hispanic (U.S. Department of Education, 2022-a).
- *Tribal Colleges or Universities (TCU):* Colleges or universities serve Native American and Alaska Native populations and are operated by tribes. The mission of these colleges or universities is to maintain, preserve, and restore Native languages and cultural traditions; offer a high-quality college education; and provide career and technical education, job training, and other career building programs (U.S. Department of Education, 2022-b).

- *Alaska Native-serving and Native Hawaiian-serving Institutions (ANNH):* Higher education institutions that aim to improve and expand their capacity to serve Alaska Native students and Native-Hawaiian students. To qualify as one of these institutions, undergraduate students who identify as Alaska Native must make up at least 20 percent of total enrollment, or students who identify as Native Hawaiian must make up at least 10 percent of total enrollment (U.S. Department of Education-c).
- *Asian American and Native American Pacific Islander-serving Institutions (AANAPISI):* Colleges or universities that aim to increase education achievement for underserved students including Asian American and Pacific Islander student populations. These intuitions have an undergraduate enrollment that is at least 10 percent Asian American and Native American Pacific Islander and at least half of the institution's degree-seeking students are denominated low-income (U.S. Department of Education, 2022-c).
- *Predominantly Black Institutions (PBI):* Higher education institutions that aim to serve more low- and middle-income Black American students. These institutions must have at least 40% African American student enrollment to be considered PBI. Differently from other group denominations, PBIs cannot intersect other MSI denominations such as HBCUs or HSIs (Jones, 2019).
- *Native American-serving Nontribal Institutions (NASNTI):* Higher education institutions that aim to improve and expand their capacity to serve Native Americans and low-income individuals. Enrollment of undergraduates in these institutions must be at least 10 percent Native American students. However, these are different from the TCU denomination, as these institutions are not controlled by tribes (U.S. Department of Education, 2022-d).

Research Motivation and Goal

Although the U.S. construction industry continues to grow, the domain still faces challenges with workforce shortages and lack of diversity. Bolstering Minority Serving Institutions (MSI), as an asset to create new pathways to educational opportunities for minority professionals, have been identified by other STEM disciplines as a potential solution for workforce shortages and diversity issues. However, MSIs are largely unexplored in construction literature. The goal of this study is to explore what MSIs provide construction degree programs and participate actively in the construction educational community. By identifying these institutions, this paper aims to contribute a new direction that the on-going discussion in academia regarding diversity, equity, and inclusion can take in construction to foster new, diverse professionals to join the workforce.

Research Methodology

An exploratory analysis was performed using existing databases that contain MSI denominated institutions under the listings by the U.S. Department of Education. The 2022 Eligibility Matrix by the U.S. Department of Education (U.S. Department of Education, 2022-e) contains a programmatic list of all institutions that meet the federal definitions for MSI program for fiscal year of 2022. The Eligibility Matrix listing contains over 900 MSI that can apply to federal grants under each corresponding minority-serving program for their respective student communities. Using the list of MSI, each institution's website was visited and investigated between April of 2022 and August of 2022 to search for the offerings of construction programs by each institution. Three key terms were used to identify construction programs on each university or college website: (1) "Construction"; (2) "Building Science"; (3) "Architecture & Engineering". Data was collected regarding the name of the program offering and the educational level of the program (e.g., Associates Degree, Bachelors, Master's). The resulting dataset was then cross referenced with the member listing of the Associated Schools of Construction (ASC) by region and the American Council for Construction Education

(ACCE) by program. The resulting programs were analyzed with descriptive statistics to understand the proportions of MSI that offer construction programs, the types of programs being offered, the degree levels of the educational programs, and the participation of MSI within the ASC and ACCE academic communities. Based on the results from the MSI exploration in construction, a discussion is provided to stress the importance of connecting with these educational institutions to increase recruitment and retention of much needed new professionals into construction careers.

Results and Discussion

Construction Degrees Offered by MSIs in the U.S

The 2022 Eligibility Matrix of the U.S. Department of Education (U.S. Department of Education, 2022-e) reports total 966 MSIs across the nation. From those institutions, the proportion of MSIs that offers construction degrees is 212 (includes institutions with overlapping denominations). From these MSIs, there are 196 unique MSI offering 2-year (AS/ASS) and 4-year (BS, MS, PhD) construction programs. Current reports show that there are 6608 institutions that offer 2-year (AS/ASS) and 4-year (BS, MS, PhD) construction programs across U.S (DataUSA, 2022). Consequently, MSIs are only 3% all institutions that offer Construction Degrees in the U.S. (Table 1). Across all seven types of MSIs, the percentage that offered construction degrees is less than 25%. The largest provider of construction degrees among the U.S. MSI is HSI (Count: 125; Percentage: 24%), followed by AANAPSI (Count: 52; Percentage: 27%), HBCU (Count: 17; Percentage: 17%), PBI (Count: 20; Percentage: 31%), TCU (Count: 6; Percentage: 17%), NASNTI (Count: 6; Percentage: 20%), and ANNH (Count: 4; Percentage: 25%) (Table 1). Most of these MSIs are geographically located in the Southern and Western States of the U.S with the exception of TCUs that are often located in the Northern Midwest and Rocky Mountains states.

Table 1. MSI Construction Program Offering Across the U.S.

Type of MSI	**MSI Count**	**Count of MSIs that Does Not Offer Construction Degrees (%)**	**Count of MSIs that Offer Construction Degrees (%)**
HSI	529	404 (76%)	125 (24%)
AANAPISI	192	140 (73%)	52 (27%)
HBCU	100	83 (83%)	17 (17%)
PBI	64	44 (69%)	20 (31%)
TCU	35	29 (83%)	6 (17%)
NASNTI	30	24 (80%)	6 (20%)
ANNH	16	12 (75%)	4 (25%)
Total	**966**	**777 (79%)**	**212* (21%)**

* *Note*: From these 212 programs, there are 196 programs due to overlap in the MSI denominations

An analysis of the 196 MSI that provide construction degrees indicates that different levels of education are offered at different MSI denominations (Figure 1). A large and significant proportion of MSI universities only offer certificate or 2-year (AS/ASS) construction programs. Some examples of programs across the U.S. that offer such degrees include University of Arkansas - Pulaski Technical College (PBI), Bay Mills Community College (TCU), Oklahoma State University Institute of Technology-Okmulgee (NASNTI). Additionally, it was found that only a small proportion of MSIs in proximity to the Hispanic communities provide 4-year (BS, MS, PhD), 2-year (AS/ASS), and Certificate construction programs. These include Florida International University (HSI), Morgan State University (HBCU), San Diego State University (AANAPISI & HIS), University of the District of Columbia (HBCU), University of Houston (AANAPISI & HSI). Moreover, it was found that only a very small portion of MSIs deliver MS and PhD degrees in construction, mostly in HSI and ANAPISI serving institutions. None of the HBCU, PBI, TCU, NASNTI, or ANNH programs were found to offer PhD programs in construction, but most offer either certificates, 2-year (AS/ASS) and 4-year BS degrees. These findings are consistent with previous reports (DataUSA, 2022) that show Hispanics represent a larger proportion of the degrees awarded compared to other minority groups.

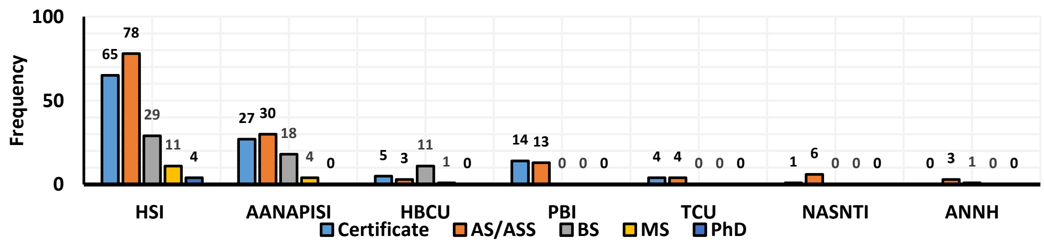

Figure 1. Educational Level by MSI Type for Construction Programs Across the U.S.

An overview of different types of construction programs offered at these MSI universities is given in Table 2. There are multiple programs offered at all MSI denominations. Overall, Construction Management programs are the most common offering across MSIs. The second most offered program across all MSIs is Construction Technology, followed by Building Construction, Construction Engineering, Architectural Engineering, and Construction Science. Variations are found with these offerings as Management and Technology degrees across MSIs. It is important to note that each MSI offers at least more than one construction program. For instance, HSIs offer a total of 157 different types of construction programs, followed by AANAPISI that offer a total of 60 programs. As some institutions can have multiple MSI denominations, there are potentially multiple programs that overlap within each institution.

Table 2. Common Construction Program Types within MSI Across the U.S.

Program Type	**Number of MSI Programs in the U.S.**						
	HSI	**AANAPISI**	**HBCU**	**PBI**	**TCU**	**NASNTI**	**ANNH**
Construction Management	55	29	7	9	0	2	2
Construction Technology	34	8	3	1	3	3	1
Building Construction	13	1	2	2	0	0	0
Construction Engineering	10	2	0	0	0	0	1
Architectural Engineering	9	4	0	0	0	0	0
Construction Science	2	0	0	0	0	0	0
Others (e.g., Building Construction Management, Construction and Civil Engineering Technology, Engineering and Construction Technology)	34	16	8	9	3	1	0
Total	157*	60*	20	25	6	6	4

* *Note*: There are multiple institutions that offer more than one program type

MSI Programs within ASC and ACCE Educational Communities

It was found that participation of MSIs in U.S. construction educational communities is small. Table 3 shows MSI construction programs that are members of the ASC. In total, there are 148 ASC members in all seven regions across the U.S., but out of 196 MSI types with construction programs, only 29 unique MSIs (15%) participate in the ASC community. Among opportunities that come with being part of ASC, students can network with other students and construction professionals, through ASC Student Competitions and Annual Conferences, and this can potentially provide a recruitment opportunity for construction contractors to get a diverse workforce. Due to the low number of MSIs that participate in ASC, the construction education community has missed opportunities to bolster diverse students and faculty into the existing events for recruitment, engagement, and participation.

Table 3. MSI Members of ASC Construction Programs

ASC Regions	**Number of ASC Schools**	**Number of MSI Programs in ASC Schools**						
		HSI	**AANAPISI**	**HBCU**	**PBI**	**TCU**	**NASNTI**	**ANNH**
1	23	0	0	1	0	0	0	0
2	21	2	0	0	0	0	0	0
3	21	0	0	0	0	0	0	0
4	16	0	1	0	0	0	0	0
5	19	7	2	0	0	0	1	0
6	26	5	1	0	0	0	0	0
7	22	9	9	0	0	0	0	0
Total	148	23	13	1	0	0	1	0

Table 4 provides an insight into MSI construction programs Accredited by ACCE. There are a total number of 90 ACCE schools on AS, BS, MS educational levels. Out of 90 ACCE accredited schools, only 20 unique MSIs (22%) are accredited by ACCE. Additional efforts by the construction education community are needed to increase the participation of MSIs in accreditation efforts. Increased accreditation participation can improve student preparation to enter the construction job market. Furthermore, of all MSI institutions in the U.S., only 14 (7%) MSIs that offer construction programs form part of both ASC and ACCE. This means that the educational community in construction has opportunities to reach out and engage MSIs to increase involvement in construction education to help address the issue of workforce shortages and diversity in construction.

Table 4. MSI Construction Programs Accredited by ACCE

Degree Level	**Number of ACCE Schools**	**Number of MSI Programs Accredited by ACCE**						
		HSI	**AANAPISI**	**HBCU**	**PBI**	**TCU**	**NASNTI**	**ANNH**
AS	15	2	0	0	1	0	0	0
BS	75	13	6	3	0	0	0	0
MS	5	0	0	0	0	0	0	0
Total	90	15	6	3	1	0	0	0

Research Limitations

There are three research limitations for this study as follows: (1) the nature of the programs identified, (2) the list of MSI used for the research, and (3) the educational communities explored. First, only three terms were used to identify construction as a major for the programs within each MSI explored (Construction, Building Science, and Architecture & Engineering). Programs that did not resemble the three terms selected for this exploratory research were not included in the analysis. Moreover, construction programs considered here were only explored as a major. It is possible that departments such as architecture and engineering have minors in construction-related disciplines. These minors in construction were not considered in the analysis. Second, student demographics across the U.S. are constantly changing and evolving. This research provides a snapshot of the programs reported by the

U.S. Department of Education for the fiscal year of 2022. The authors are aware that multiple institutions within the ASC and ACCE educational communities obtained their MSI designation during the 2022 year (e.g., Arizona State University, University of Texas A&M) and these are not included in the analysis of this manuscript. Third, only ASC and ACCE educational communities were explored in this paper.

Conclusion and Recommendations

The demand of new professionals into construction careers continues to grow as the industry faces workforce shortages. The lack of diversity in the construction workforce has been identified as one of the factors that influences the low influx of new professionals into the discipline. This study explores what Minority Serving Institutions (MSIs) are actively engaged in the construction education community. The results obtained from an exploratory analysis indicate that only 3% of the U.S. MSIs offer Construction Degrees. Most of these MSI universities are geographically located in the Southern and Western States of the U.S. A small percentage of MSI offers 4-year BS, and MS, PhD programs, with a majority of MSI only offering certificate or 2-year (AS/ASS) in construction. Different construction program types are offered at these MSI universities, largely centered in Construction Management. The participation of MSIs in the construction educational community is small, with low percentages of participation in ASC and ACCE communities. These results indicate that there are large opportunities to engage MSIs to attract new, diverse professionals in construction. It is pivotal to explore how to get more MSIs involved into educational communities such as the ASC and ACCE. These educational institutions offer opportunities to increase recruitment and retention for the construction industry. Therefore, it recommended to establish a taskforce within ASC for Diversity, Equity, and Inclusion (DEI). This new ASC taskforce can create concerted efforts to connect with MSIs that have existing construction programs to get them involved in the academic community. Moreover, the ASC DEI taskforce can ask MSIs regarding their institutional challenges to participate in ASC and get accredited through ACCE. By answering this questions, new MSI members can be encouraged by providing support from ASC and ACCE to become part of the community and potentially foster the creation of new construction programs or expansion of existing ones. We believe the intentional engagement of MSIs would inform ASC community of the actual challenges and effective solutions for students to enter and stay in construction careers, and how the communication can promote DEI into the workforce.

References

Al-Bayati, A. J., Abudayyeh, O., Fredericks, T., and Butt, S. (2017) “Managing Cultural Diversity at U.S. Construction Sites: Hispanic Workers’ Perspectives." Journal of Construction Engineering and Management. DOI: 10.1061/(ASCE)CO.1943-7862.0001359DataUSA (2022). Construction Institutions, Employment, Diversity, and Skills. Retrieved from: https://datausa.io/profile/cip/construction-46#institutions (Last accessed on: 9/21/2022)

Toppin, I. (2018). Who is going to build the wall? A building trades crisis in the U.S. Int. Journal for Research in Vocational Edu. and Tra., 5(1), 64–76. https://doi.org/10.13152/ijrvet.5.1.4

Suryadi, J. (2018). Examining the Labor Shortage in the Construction Industry and Possible Solutions Presented by Industry Members. Honors Thesis, California Polytechnic University, San Luis Obispo. Retrieved From: https://digitalcommons.calpoly.edu/cgi/viewcontent.cgi?article=1187&context=cmsp (Last accessed on 9/21/2022).

U.S. Bureau of Labor Statistics (BLS) (2022-a). Occupational Outlook Handbook: Construction and Extraction Occupations. Retrieved from: https://www.bls.gov/ooh/construction-and-extraction/home.htm (Last accessed on 9/26/2022).

U.S. Bureau of Labor Statistics (BLS) (2022-b). Occupational Outlook Handbook: Construction Managers. Retrieved from: https://www.bls.gov/ooh/management/construction-managers.htm (Last accessed on 9/26/2022).
U.S. Bureau of Labor Statistics (BLS) (2022-c). Labor Force Statistics from the Current Population Survey. Retrieved from: https://www.bls.gov/cps/cpsaat18.htm (Last accessed on 9/23/2022).
U.S. Bureau of Labor Statistics (BLS) (2022-d). Occupational Outlook Handbook: Architectural and Engineering Managers. Retrieved from: https://www.bls.gov/ooh/management/architectural-and-engineering-managers.htm (Last accessed on 9/26/2022).
Manesh, S. N., Choi, J. O., & Shrestha, P. (2020). Critical Literature Review on the Diversity and Inclusion of Women and Ethnic Minorities in Construction and Civil Engineering Industry and Education. In CRC 2020 (pp. 175-184). Reston, VA: ASCE.
National Center for Construction Education & Research (NCCER) (2020). Research & Marketing Playbook for the Construction Industry. Retrieved from: https://nccer.actonservice.com/acton/fs/blocks/showLandingPage/a/29279/p/p-0026/t/page/fm/0 (Last accessed on 9/21/2022)
Bigelow, B. F., Saseendran, A., & Elliott, J. W. (2018). Attracting students to construction education programs: An exploration of perceptions by gender. International Journal of Construction Education and Research, 14(3), 179-197.
Choi, J.O., Shane, J.S., Chih Y. (2022). Special Collection Announcement: Diversity and Inclusion in the Engineering-Construction Industry. ASCE Journal of Mgmt. in Eng., 2022, 38(2).
Fry, R., Kennedy, B., & Funk, C. (2021). STEM jobs see uneven progress in increasing gender, racial and ethnic diversity. Pew Research Center.
National Academies of Sciences, Engineering, and Medicine (NASME). (2019). Minority Serving Institutions: America's Underutilized Resource for Strengthening the STEM Workforce. Washington, DC: The National Academies Press. https://doi.org/10.17226/25257
U.S. Department of Labor. (2021). Registered Apprenticeship National Results Fiscal Year 2021. Retrieved from: https://www.dol.gov/agencies/eta/apprenticeship/about/statistics/2021 (Last accessed on: 9/27/2022).
U.S. Department of Education (2011). Higher Education Resources and Student Assistance. Retrieved from: https://www.govinfo.gov/content/pkg/USCODE-2011-title20/html/USCODE-2011-title20-chap28-subchapIII-partE-subpart3-sec1067k.htm (Last accessed on: 9/27/2022).
National Center for Education Statistics (NCES) (2020). Fast Facts: Historically Black Colleges and Universities. Retrieved from: https://nces.ed.gov/fastfacts/display.asp?id=667 (Last accessed on 9/27/2022).
U.S. Department of Education (2022-a). White House Initiative on Hispanic-Serving Institutions (HSIs). Retrieved from: https://sites.ed.gov/hispanic-initiative/hispanic-serving-institutions-hsis/ (Last accessed on 9/27/2022).
U.S. Department of Education (2022-b). White House Initiative on Native Americans and Strengthening Tribal Colleges and Universities. Retrieved from: https://sites.ed.gov/whiaiane/tribes-tcus/tribal-colleges-and-universities/ (Last accessed on 9/27/2022).
U.S. Department of Education (2022-c). Lists of Institutions Enrolling Populations with Significant Percentages of Undergraduate Minority Students. Retrieved from: https://www2.ed.gov/about/offices/list/ocr/edlite-minorityinst.html (Last accessed on 9/27/2022).
U.S. Department of Education (2022-d). White House Initiative on Native Americans and Strengthening Tribal Colleges and Universities. Retrieved from: https://sites.ed.gov/whiaiane/nasntis/#:~:text=A%20Native%20American%20Serving%20Non,a%20Tribal%20College%20or%20University (Last accessed on 9/27/2022).
U.S. Department of Education (2022-e). MSI Eligibility Matrix. Retrieved from: https://www2.ed.gov/about/offices/list/ope/idues/eligibility.html (Last accessed on: 9/21/2022)
Jones, B. (2019). Predominantly Black Institutions: Pathways to Black student educational attainment. CMSI Research Brief, Philadelphia, PA, 1.

Using Drones to Attract K-12 Students Towards Construction: A Pilot Study of Middle School Students' attitudes, Perceptions, and Interests

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Drones continue to support the growth of the construction industry; however, activities that use drones for K-12 education are still minimal and exploratory. Particularly, no studies have explored the use of drone technologies to attract students towards construction disciplines. The contribution of this study centers on better understanding how drones can be relied upon to create interest and motivation in K-12 students by showcasing the construction domain to the next generation of the workforce. This study investigated the attitudes and interests towards construction of eleven middle school students enrolled in a Summer Youth Camp at the Michigan Technological University. During this study, a construction-centric drone education activity was designed and implemented during a 3-hour long session within a large lab space. Students completed an adapted version of the S-STEM Survey before and after participating in the activity. Although differences in the survey scores for attitudes towards STEM subjects and interests in construction careers were noticed, no significant changes were observed by the educational activity. Ultimately, this study recommends the use of drones in K-12 activities and purposes exploring how students can be attracted to the construction disciplines as future research.

Key Words: Construction Drones, K-12 Education, Attitudes, Interests, Career Pathways

Introduction

Construction is one of the largest adopters of drones for commercial tasks (DroneDeploy, 2018). This increased drone usage in construction has been linked to the aerial robots' capability to access unreachable or unsafe areas and perform tasks safely and time-efficiently (Albeaino & Gheisari, 2021). Even though technological advances such as drones are helping construction grow as an industry, reports continuously show problems with workforce labor shortages (Olsen et al., 2012). These workforce shortages are the result of older professionals leaving the industry once they reach retirement age and a low influx of new professionals (Suryadi, 2018). Researchers indicate that there are large difficulties to engage and retain new students in the construction disciplines (Bigelow et al., 2018). Some studies report that there are negative perceptions (e.g., physically demanding, limited career progression, unsafe) of the construction industry, with over 70% of parents indicating that they would not advise their children to pursue construction careers (NCCER, 2020). Other researchers point to the lack of representation of women, minorities, and persons with disabilities in a largely white, male-dominated industry sector (Manesh et al., 2020) and that students simply do not get sufficient exposure to the industry in terms of career exploration, work experiences, or field trips (Bigelow et al., 2018).

Drones and robotics in the education domain have been used effectively to engage students and foster interest in STEM careers. Middle school students are often the focus of these investigations within the context of drone and robotics activities, as research has shown that students at this age-range start to develop interests in STEM and begin to consider career aspirations (Almeda & Baker, 2020). To engage middle school students, drone and robotics education leverages extracurricular events such as competitions, workshops, and after-school programs (Ribeiro & Lopes, 2020). These events have been successfully implemented in a limited number of STEM disciplines (e.g., computer science, mathematics) to increase motivation and engagement (Chou, 2018; Bartholomew & Mayo, 2018) as well as self-efficacy and interest (Tezza et al., 2020).

To address the growing need to engage a new generation of construction professionals, the goal of this study is to explore the utilization of drones to attract middle school students towards considering construction as a career path. A pilot intervention was designed and implemented using construction-centric contents and drones to achieve this goal. Middle school students' attitudes, perceptions, and interests towards construction were captured before and after a pilot educational intervention. The contribution of this study centers on better understanding how drones can be used to create interest and motivation in K-12 students by showcasing the construction domain to the next generation of the workforce.

Background

Drones – also known as unmanned aerial vehicles (UAVs) or unmanned aerial systems (UASs) – are defined as remotely piloted aerial robotic platforms equipped with several onboard sensors (Albeaino & Gheisari, 2021). In the construction domain, drones are being used in different phases, from pre-construction (e.g., site planning, site mapping and surveying), construction (building inspection, safety management), to post-construction (building maintenance, post-disaster reconnaissance) (Albeaino & Gheisari, 2021). These type of drone applications in construction have been recognized to save time, improve accessibility to compromised spaces, and reduce the cost of construction tasks (Gheisari & Esmaeili, 2019).

In the educational domain, drones have been found to promote engagement, motivation, and interests through the use of active, hands-on experiences (Sattar et al., 2017). Literature has identified that drones can help students to transform abstract concepts into concrete learning (Tezza et al., 2020), develop technical knowledge and skills (Chou, 2018), and acquire positive attitudes towards STEM disciplines (Yousuf et al., 2019). Existing drone-based curricula designs provide opportunities to understand the concepts of drones, use drones to accomplish some tasks (e.g., drone building, flying, collecting data, programming), and conclude by reflecting on the acquired knowledge (Chou, 2018; Bartholomew & Mayo, 2018; Tezza et al., 2020). To implement these curricula, researchers and educators have utilized tangible drone hardware in combination with software tools for student experimentation in laboratory or classroom environments (Khan, 2018; Chun, 2021).

Activities that use drones in the construction education domain are still minimal and exploratory. Most existing activities in construction drones are mainly focused on higher education settings, teaching college and university students drone regulations, flight operations, data collection, and data processing (Eiris et al., 2018; Williamson III & Gage, 2019; Albeaino et al., 2022). Drone activities in disciplines such as computer sciences, Mathematics, and aviation are situated within the context. For example, computer sciences can do drone programming, Mathematics can do problem solving, and Aviation can do drone flying. However, we have many constraints in construction due to legal and safety concerns. Drone flights introduce liability and legal concerns, ranging from personal injury and property damage caused by drone operation errors, to issues such as invasion of privacy, trespassing, property rights, or insurance issues (Gheisari and Esmaeili 2019). Moreover, taking students to construction sites is inherently difficult, as construction remains one of the most dangerous industries.

Research Motivation and Scope

The construction industry is in great need for a new generation of construction professionals to join the workforce. Although, drones have been shown to have the capability to produce interest and engagement in K-12 students (Burack et al., 2019), there are no studies that investigate how to expose students to construction drones prior to their enrollment in higher education programs. This study discusses the design and implementation of a construction-centric drone K-12 educational activity to engage students at an early age. Particularly, middle school students were targeted, as students in this age range start to develop career interests (Almeda & Baker, 2020). A pilot pre-, post- experimental design was used to measure attitudes, perceptions, and interest metrics through a validated survey.

Research Methodology

Educational Context for Construction-Centric K-12 Drone Intervention

For this study, an educational activity for drones in construction was planned as part of a Summer Youth Program at the Michigan Technological University (MTU). The Summer Youth Program at MTU offers K-12 students' hands-on explorations of STEM disciplines within campus. Students enroll in a week-long program based on their preferences and the departmental offerings at MTU. Multiple activities occur each morning and afternoon of the program, guided by faculty, staff, and graduate students. The drone activity in this study was hosted within the "Building a Better World" program in partnership with the Civil, Environmental, and Geospatial Engineering Department at MTU. From the K-12 educational range, only students from 6th to 9th grade participated. This study took place in a three-hour, three-part module on the morning of the second day within the week-long program. The educational intervention was constrained and driven by this context and time module requirements. Following is a description of design and implementation of the activity for this pilot study.

Construction Educational Activity Design and Implementation

The education activity to expose K-12 students to construction disciplines was designed based on the existing STEM literature that recommends three major components: (1) providing an understanding of the drone concepts, (2) using drones to accomplish some tasks (e.g., drone building, flying, collecting data), and (3) offering a reflection activity from the acquired knowledge (Chou, 2018; Bartholomew & Mayo, 2018; Tezza et al., 2020). To achieve these components of previously successful K-12 drone STEM activities, three modules were designed as shown in Figure 1.

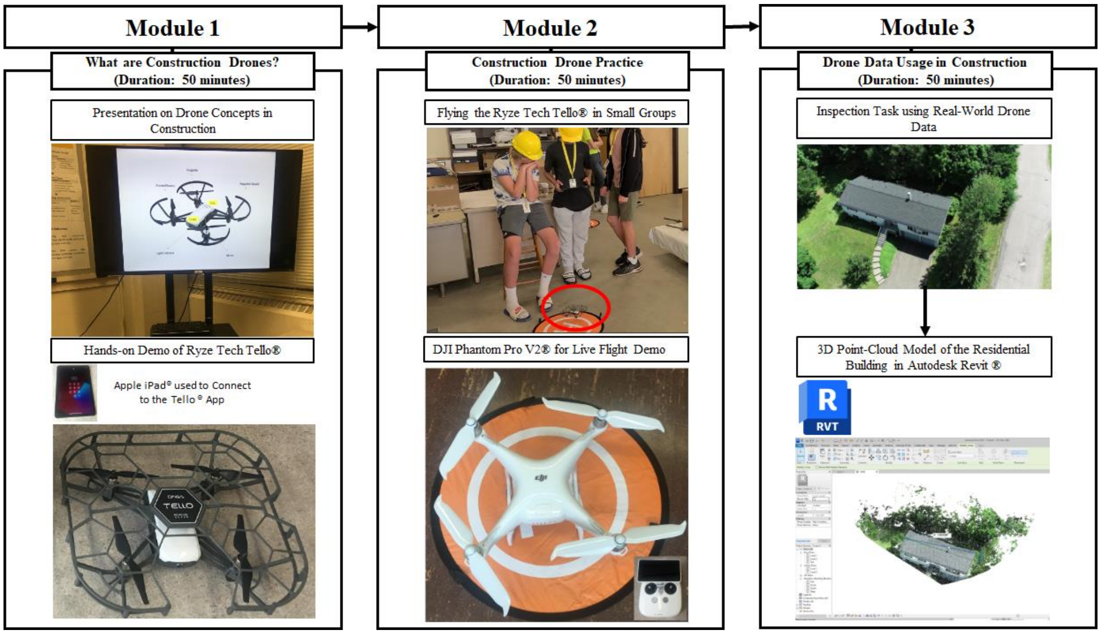

Figure 1. Construction Drones Educational Activity Design

Module 1 – What are Construction Drones? – This module focused on introducing construction drones to students. A discussion was provided regarding the different parts of drones (e.g., propellers, batteries, data capturing sensors), construction drone applications using multiple sensors (e.g., building inspection task, quantity takeoffs, energy monitoring), and drone flight safety requirements on construction sites. Additionally, an introductory description of the basic flight operations was delivered for students prior to practicing their drone flight skills.

Module 2 – Construction Drone Practice – This module enabled students to perform hands-on flight employing a Category 1 drone (less than 0.55 pounds; Ryze Tech Tello®) in an indoor lab environment. The flight task was inspired by construction building inspection tasks, requiring pilots to observe objects using an onboard camera sensor during a drone flight. Moreover, in this module, students learned about construction drone flight operations and applications through a live flight.

Module 3 – Drone Data Usage in Construction – This module offered students the opportunity to reflect on prior modules by using drone collected data. Through the use of Autodesk Revit®, students performed a building inspection task using a point-cloud model of a residential building. A discussion was held regarding the use of drones in construction through the data visualization task, elaborating on the dimensions necessary to add a garage to the house project.

The implementation of this construction drone educational activity was done after approval from the MTU Internal Review Board (IRB-1912793-2). Prior to the activity, parents and students provided informed consent through an established protocol. The duration of the activity and the data collection totaled 3 hours. Each module lasted for approximately 50 minutes and the data collection took 15 minutes before and after the drone activities. Before starting the construction drone educational activity, a demographic questionnaire, and an attitudes, perceptions, and interest survey were completed by the students. After completing the drone activity, the same attitudes, perceptions, and interests survey was completed again. To make sure all operations were safe for the students, all flights were conducted with a drone less than 0.55 pounds (Category 1), with a safety cage blocking any exposed rotating parts that could lacerate human skin. Additionally, hardhats and safety glasses were required at all times. All activities were overseen by a Federal Aviation Administration (FAA) – Part 107 remote pilot certificate holder. The activity modules were held in an indoor, controlled laboratory space. Five Ryze Tello® drones and Tello® Propeller Guards were used for Module 2. Students were split into small teams of three, each using one drone battery that delivers 10 to 15 minutes of flight time. All students used the Tello® companion app in an Apple iPad® device to operate the drones.

Activity Evaluation and Metrics

To measure students' attitudes, perceptions, and interest towards construction, this study utilized a pre-, post-test experimental design. Students completed an adapted version of the Middle/High School (6^{th} – 12^{th}) Student Attitudes towards Science, Technology, Engineering, and Math (S-STEM) Survey (Unfried et al., 2015). This survey measures changes in student attitudes and perceptions in STEM subjects, and interests in STEM careers. Adapted version of the S-STEM survey was used in this study, consisting of 25 items divided into two sections. The first section of the survey had 18 items with a 5-point Likert scale measuring students' self-perception and attitudes towards STEM subjects across three dimensions – Math, Science, and Engineering. The Math dimension contained five questions that were rated between 1 = Strongly Disagree, and 5 = Strongly Agree. The Science dimension contained five questions that were rated between 1 = Strongly Disagree, and 5 = Strongly Agree. The Engineering dimension contained eight questions that were also rated between 1 = Strongly Disagree, and 5 = Strongly Agree. The survey questions used statements that revealed how the students perceive themselves in relation to Math, Science, and Engineering (e.g., I am good at math; I know I can do well in science; I am curious about how to construct things). The second section of the survey used a 4-point Likert scale used to measure participants' interests in STEM and construction careers. The survey question in this second section described potential careers (e.g., Energy, Computer Science, Construction) and students rated their interests using a scale between 1= Not at all interested, and 4 = Very interested. Each career name included its definition and short description of their work environment.

Results and Discussion

Demographics

A total of 14 middle school students participated in the construction drone activity during the Summer of 2022. From the 14 student participants, the data from 3 had to be discarded due to incomplete responses. The remaining 11 participants (2 females and 9 males) were considered for analysis in this study. In terms of participant demographics (Table 1), students ranged in age from 12 to 14 years, with a mean age of 13 years. The sample collected included students in grades 7^{th} through 9^{th}, with the majority (55%) being in 8^{th} grade. The majority of participants were male (82%), and a small portion female (18%). Most participants identified as White (73%), with a small percentage identifying as other races (27%) (Asian, Indian, and 1 Unspecified). A large percentage of the students reported to have used a drone more than once before (82%).

Table 1. Demographic information on Construction-Centric K-12 Drone Intervention participants

Participants	**Categories**	**Number**	**Percentage**
Sex	Male	9	82%

	Female	2	18%
Age	Years	12-14	13
Race	White	8	73%
	Other (e.g., Asian, Indian, and 1 Unspecified)	3	27%
Grade	7th	2	18%
	8th	6	55%
	9th	3	27%
Have you ever used a drone before?	No, Never	1	9%
	Only Once	1	9%
	A few times	9	82%

Attitudes and Interests

The data from pre- and post-test survey for the construction drone activity was analyzed with both descriptive and inferential statistics. Table 2 shows the results from this analysis. A lower mean score was obtained in the post-test attitudes and perception towards STEM subjects compared with the pre-test results for Math (pre = 4.61; post = 4.39; delta = 0.22), Science (pre = 4.11; post = 3.99; delta = 0.12), and Engineering (pre = 4.19; post = 4.11; delta = 0.08). The largest score differential observed was for Math (delta = 0.22) and the lowest overall score means were obtained for Science (pre = 4.11; post = 3.99). These attitudes and perception results for the Math and Science dimensions of the survey can be potentially attributed to the lack of student exposure in the construction drone activity to Math or Science topics as typically done in a middle classroom setting (e.g., algebra problems, reading assignments). Overall, both Math and Engineering scores were observed positive, with a mean score above 4 (Agree) on the Likert scale of pre- and post-test survey. For the test results on interests in STEM careers, it was found that the mean scores where high for all careers. It is important to highlight that the pre- and post-test results for interest in Engineering (pre = 2.73; post = 3.27; delta = 0.54) and Construction (pre = 2.91; post = 3.27; delta = 0.36) careers show the largest mean scores among all the survey careers (both pre and post-test). These career interest results could be explained by the fact that the designed construction drone activity offered direct exposure to the construction domain, while no exposure to the other careers in the survey was offered to the students.

The inferential statistical analysis was performed using a paired-samples t-test. This statistical analysis revealed that there were no significant differences in the attitudes and perceptions students regarding STEM subjects, or in the interest in STEM and Construction careers due to the construction drone activity. The lack of significant differences between pre-test and post-test could be explained by a small sample size. Although the construction drone activity data set only contained 11 students, the results of this study suggest that there might be positive relation between interest in STEM and Construction careers and the experiences offered by the construction drone activity.

Table 2. Adapted S-STEM Survey for Attitudes and Interests

Categories	**Pre-test**	**Post-test**	**P-value**
	Mean (SD)	**Mean (SD)**	
Attitudes towards STEM Subjects			
Math	4.61 (0.19)	4.39 (0.17)	0.23
Science	4.14 (0.16)	3.94 (0.09)	0.15
Engineering	4.19 (0.26)	4.11 (0.18)	0.48
Interests in STEM Careers			

Biology and Zoology	2.41 (0.10)	2.64 (0.11)	0.69
Mathematics	2.45 (0.11)	3.00 (0.11)	0.31
Computer Science	2.55 (0.10)	3.00 (0.08)	0.30
Chemistry	2.45 (0.08)	2.73 (0.09)	0.49
Energy	2.45 (0.10)	3.18 (0.07)	0.12
Engineering	2.73 (0.12)	3.27 (0.08)	0.14
Construction	2.91 (0.09)	3.27 (0.08)	0.37

Lessons Learned: Opportunities and Challenges

Opportunities: Throughout the construction drone activity, students displayed engagement and excitement. Module 2 – Construction Drone Practice, was observed to be the most engaging of the activities to the students. Additionally, students displayed excitement about construction drones through asking questions such as the drone costs, and taking pictures and videos while flying the drones in the lab space. These observations regarding the hands-on nature of drone activities match what prior studies have found in terms of drone effectiveness to attract students towards STEM disciplines (Chou, 2018; Bartholomew & Mayo, 2018). It was also found that the simplicity and accessibility of the Ryze Tello® drones enable the completion of the activities without major issues for the duration of the activity. These drones were easy to fly and students quickly learned how to employ the camera sensor to capture data within the lab space. Moreover, there was institutional and parental buy-in to perform this activity. MTU provided the funds needed to perform this study and all parents authorized their children to participate in the activity. It is particularly important to get parents' interest, as research shows that parental approval significantly influences student engagement and motivation in STEM (Bempechat & Shernoff, 2012).

Challenges: Despite the educational opportunities learned from this study, there were several challenges observed. Although the drones selected were suitable for this type of study, there were limitations in terms of flight time and network interference from multiple Ryze Tello® drones. During the "Module 2 – Construction Drone Practice", several flight interruptions were experienced during the practice event. These interruptions occurred due to network issues with connection between the ground control station and the drones, producing sudden disconnections and loss of control of the drone. Another challenge faced by the researchers was the limited amount of time for the activity. The overall activities lasted for three hours in a single exposure. This limited amount of time reduced the ability of students to internalize the learned contents and constrained the design of the module to very simple topics in construction and drones. A more comprehensive curriculum with a longer exposure time (e.g., few days) is recommended to increase the effectiveness of such activities to engage, motivate, and attract students towards construction.

Research Limitations

In disciplines such as computer science, mathematics, and aviation, drone activities are situated within the context of their corresponding domains. For example, computer science students can get direct exposure to programming using drones, mathematics students can do problem solving, and aviation perform drone flights. However, construction disciplines students do not get direct exposure to jobsites due to legal and safety issues. These constraints can potentially contribute to lower impact on student engagement for construction in comparison to other disciplines. This study had several limitations related to the sample size, the limited exposure time, and the lack of exposure to real-world drone operations. First, the sample size was small and lacked diversity. The sample composition consisted of only 7th through 9th grade middle school students with most of the participants (73%) being from one race (White). Additionally, the sample ratio of male-to-female was disbalanced, with a very small proportion of females (18%). Second, this study took place in a three-hour module on the second day of the week-long program. The educational activity was constrained and driven by this context and time each module required. Third, the drone activity design and implementation of this study was not situated in a real-world construction site. The lack of exposure to construction sites was due to safety concerns for flying drones by a large group of middle school students. This is a common limitation of educational studies in higher education (Eiris et al., 2018; Williamson III & Gage, 2019; Albeaino et al., 2022) that extends into this exploratory study.

Conclusion and Future Study

Although drones continue to support the growth of the construction industry, no studies have explored how to employ drone technologies to attract K-12 students towards construction disciplines. An experimental K-12 activity was designed to enhance students' attitudes and perceptions towards construction, as well as to provide a method to foster interest in construction domain careers. The created K-12 educational activity was piloted with eleven middle school students, introducing them to construction drones, allowing them to perform hands-on flight operations, and offering them opportunities to reflect on drone-collected data through the use of point-clouds. Data was collected from the middle school students before and after exposing them to the construction drone activity through the use of an adapted version of the S-STEM Survey (Unfried et al., 2015). The S-STEM survey measured changes in attitudes, perceptions, and interest regarding STEM and construction. The results obtained from the pilot study showed mean score differences in attitudes and perceptions towards STEM, and interests in construction careers. However, these results did not show statistically significant differences, mainly due to the small study sample size.

We concur with previous researchers that drones can be effective in attracting students towards construction as it has worked in other disciplines (Bartholomew & Mayo, 2018; Khan, 2018; Yousuf et al, 2019; Tezza et al, 2020). Our results provide hints that drones might enable to engage students in construction. However, further research is necessary to definitively answer this question. Future studies exploring the attraction of K-12 students to construction disciplines should adapt the design provided in this study for a larger cohort of participants. By collecting a larger sample with more robust gender and racial/ethnic diversity, researchers would be able to understand what aspects of drones and construction attract different types of students to construction. Furthermore, there is a need to understand how exposure to real-world drones, actual construction sites, and practicing construction professionals might enhance the design of the presented activity. Finally, other variables such as knowledge, engagement and motivation, and self-efficacy should be explored to better understand the mechanism that changes in students' attitudes, perceptions, and interests towards construction.

References

DroneDeploy (2018). 2018 Commercial Drone Industry Trends. Retrieved from: https://dronedeploy-www.cdn.prismic.io/dronedeploy-www%2Fae535fda-dfc9-4bcf-9743292df714e9fe_dd__2018_trends__report-f.pdf (Last accessed on 9/21/2022)
Albeaino, G., Gheisari, M., & Issa, R. R. (2022). Integration of a UAS-Photogrammetry Module in a Technology-based Construction Management Course. EPiC Series in Built Env., 3, 497-505.
Gheisari, M., & Esmaeili, B. (2019). Applications and requirements of unmanned aerial systems (UASs) for construction safety. Safety Science, 118, 230–240.

Albeaino, G., Eiris, R., Gheisari, M., & Issa, R. R. (2022). DroneSim: A VR-based flight training simulator for drone-mediated building inspections. Construction Innovation.

Albeaino, G., & Gheisari, M. (2021). Trends, benefits, and barriers of unmanned aerial systems in the construction industry: a survey study in the United States. Journal of Information Technology in Construction (ITcon), 26(6), 84-111.

Manesh, S. N., Choi, J. O., & Shrestha, P. (2020). Critical Literature Review on the Diversity and Inclusion of Women and Ethnic Minorities in Construction and Civil Engineering Industry and Education. In Construction Research Congress 2020: Safety, Workforce, and Education (pp. 175-184). Reston, VA: American Society of Civil Engineers.

Suryadi, J. (2018). Examining the Labor Shortage in the Construction Industry and Possible Solutions Presented by Industry Members. CalPoly, SLO. Retrieved From: https://digitalcommons.calpoly.edu/cgi/viewcontent.cgi? article =1187&context=cmsp (Last accessed on 9/21/2022).

Olsen, D., Tatum, M., and Defnall, C. (2012). How industrial contractors are handling skilled labor shortages in the United States. 48th ASC Annual International Conference Proceedings.

Bigelow, B. F., Saseendran, A., & Elliott, J. W. (2018). Attracting students to construction education programs: An exploration of perceptions by gender. International Journal of Construction Education and Research, 14(3), 179-197.

National Center for Construction Education & Research (NCCER) (2020). Research & Marketing Playbook for the Construction Industry. Retrieved from: https://nccer.actonservice.com/acton/fs/blocks/showLandingPage/a/29279/p/p-0026/t/page/fm/0 (Last accessed on 9/21/2022)

Burack, C., Melchior, A., & Hoover, M. (2019). Do After-School Robotics Programs Expand the Pipeline into STEM Majors in College?. Journal of Pre-College Eng. Edu. Research, 9(2), 7.

Almeda, M. & Baker, R.S. (2020). Predicting Student Participation in STEM Careers: The Role of Affect and Engagement during Middle School. Journal of Edu. Data Mining, 12(2), 33-47.

Ribeiro, A. F., & Lopes, G. (2020). Learning robotics: a review. Current Robotics Reports, 1(1), 1-11.

Chou, P. N. (2018). Smart technology for sustainable curriculum: using drones to support young students' learning. Sustainability, 10(10), 3819.

Bartholomew, J. L., & Mayo, R. S. (2018). Development of a 4th-8th grade curriculum for flying and programming mini drones. Master of Science Thesis, Utah State University.

Tezza, D., Garcia, S., & Andujar, M. (2020). Let's Learn! An Initial Guide on Using Drones to Teach STEM for Children. International Conference on HCI (pp. 530-543).

Sattar, F., Tamatea, L., & Nawaz, M. (2017). Droning the pedagogy: Future prospect of teaching and learning. International Journal of Educational and Pedagogical Sciences, 11(6), 1632-1637.

Yousuf, A. Mustafa, M.A., Hayder, M.M., & Cunningham, K.R. (2019) Drone Labs to Promote Interest in STEM. 2019 126th ASEE Annual Conference and Exposition, June 16-19.

Chun, H. (2021). A Study on the Utilization of Drone Education in the Fourth Industrial Revolution. In Journal of Physics: Conference Series (Vol. 1875, No. 1, p. 012017). IOP Publishing.

Khan, M. J. (2018). Impact of Programming Robots and Drones on STEM Attitudes. 2018 ASEE Annual Conference and Exposition, June 24-27, Salt Lake City, UT.

Williamson III, K.C., & Gage, G. (2019) Important Considerations for Implementing a Drone-based Activity within a Construction Surveying Course. Annual Conference for the Associated School of Construction Denver, Colorado, Apr. 2019.

Eiris, R., Zhou, S., & Gheisari, M. (2018). Integrating the Use of UAVs and Photogrammetry into a Construction Management Course: Lessons Learned. International Symposium on Automation and Robotics in Construction (ISARC) Jul. 2018

Bempechat, J., & Shernoff, D. J. (2012). Parental influences on achievement motivation and student engagement. In the Handbook of research on student engagement (pp. 315-342). Springer.

Unfried, A., Faber, M., Stanhope, D. S., & Wiebe, E. (2015). The development and validation of a measure of student attitudes toward science, technology, engineering, and math (S-STEM). Journal of Psychoeducational Assessment, 33(7), 622-639.

Knowledge and Skills Required for NZEB Project Construction

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Efficient project management is crucial to project success. As the construction industry changes, constructors face new issues and must undertake roles that have not traditionally been part of their responsibility. The aim of this study was to identify the Net Zero Energy Building (NZEB) project management challenges, and to determine the knowledge areas and skills that are necessary to respond to those challenges through surveys and interviews with NZEB constructors. NZEBs consume less resources than produced during operations of the building. Results revealed that the most important challenges were a general unawareness of the correct methods and procedures, reluctance to change from traditional practices, and the lack of the technical skills with NZEB technologies. The most important knowledge areas identified were communication management, schedule management and planning, and cost management. The most important skills were teamwork, leadership, and problem-solving. In addition, this study provides a summary of the importance of the various mechanisms for professional constructors' development of net zero construction knowledge and skills. This study is beneficial for the constructors' decision making in the NZEB project context. Educators are also expected to benefit from this study in the development of academic curriculum with a goal to meet the need.

Key Words: Green Construction, Net Zero, NZEB, Construction Knowledge and Skills.

Introduction

With the increasing global concern for the negative impacts brought upon the environment by human activities in recent years, many industries are turning towards implementing sustainability and green measures. The construction industry consumes a significant amount of energy and emits greenhouse gases (GHG), which are among the key factors for global warming. According to the United States Environmental Protection Agency's 2021 Annual Report (EPA, 2021), buildings are responsible for nearly 40% of the energy consumed and over 30% of GHG emissions in the United States. To mitigate the negative impacts on the environment, facility owners are looking to build facilities that will operate with reduced levels of energy consumption and natural resources across the building life cycle. As a result, many construction companies have integrated green concepts into their construction plans. Initially green buildings were intended to reduce the negative impacts on the environment caused by the building industry. In recent years, the design and construction industry has expanded its green building efforts toward “net-zero”, which simply means consuming less resources than produced (U.S. Green Building Council, 2014). As the green and net zero building construction continues to grow, there is a need to better understand what is needed by project constructors to manage net zero building construction. This study’s aim was to identify the challenges of NZEB project management, and the essential knowledge and skills required for construction professionals to successfully deliver NZEB projects.

Background

Based on a comprehensive literature review, Hwang and Ng (2013) summarized the major challenges that project managers face in managing green construction projects. Those were 1) higher costs for green construction practices and materials, 2) technical difficulty during the construction process, 3) risk due to different contract forms of project delivery, 4) lengthy approval process for new green technologies and recycled materials, 5) unfamiliarity with green technologies, 6) greater communication and interest required amongst project team members, and 7) more time required to implement green construction practices on site. Additionally, Marcelino-Sádaba, González-Jaen, and Pérez-Ezcurdia (2015) identified communication, stakeholders, costs, risks and deadlines as the areas with the greatest impact on the project management of green construction.

The Project Management Institute documented nine knowledge areas in its Guide to the Project Management Body of Knowledge (PMBOK, 2017). Those areas are integration, time, cost, procurement, quality, communication, human resource, scope, and risk. Each of the nine knowledge areas contains processes that need to be accomplished within a discipline to achieve an effective project management program. For instance, project cost management encompasses processes that are required to ensure the project is completed within the approved budget and consists of resource planning, cost estimating, cost budgeting, and cost control. Likewise, project risk management is the process concerned with identifying, analyzing, and responding to project risk (Hwang & Ng, 2013). Dogbegah, Owusu-Manu, and Omoteso (2011) conducted a study on project management competencies for the construction industry and identified an additional six project management competencies, which were human resource management and project control, construction innovation and communication, project financial resources management, project risk and quality management, business ethics and physical resources, and procurement management.

Edum-Fotwe and McCaffer (2000) stated that acquiring the knowledge inputs for a particular type of project enables the project manager to develop two types of skills, which are specific skills and general skills. Specific skills relate directly, and only, to construction projects and the areas that reflect their specialty. Whereas, general skills are transferable from one type of construction project to another. According to Hwang and Ng (2013), most of the earlier research papers share similarities in that they identified direct and indirect skills that affect the construction professional’s competencies. Direct skills are associated with one’s technical competencies that have a direct influence on project performance. For instance, project planning is a specific direct skill that is utilized for scheduling construction activities. Indirect skills such as managerial effectiveness, for example, have an indirect influence on project performance and are needed as much as direct skills to ensure that workers on a job site execute their work to meet the project's deadline.

Previous studies focused on identifying the factors specific to the technical, cost, and organizational aspects of a green building project. A comprehensive study on the factors affecting the success and failure of managing NZEB building projects is lacking. This study identified the project management challenges, knowledge and skills needed to successfully deliver NZEB projects. The categories of professional development were also examined. Understanding the importance of these professional development categories will provide information for use in the design and development of educational and training programs.

Methodology

A convergent mixed method study was conducted for an in-depth understanding of the NZEB project management challenges, and the knowledge and skills that construction professionals need to successfully deliver NZEB projects. The two parts of the study were: 1) a structured survey to generate the quantitative data, and 2) an interview using a semi-structured questionnaire to generate the qualitative data. Thus, both quantitative and qualitative data were collected and analyzed. After analysis of all the data was complete, the results of the analyses were compared for interpretation and explanation. Figure 1 shows a diagram depicting the convergent design of this study.

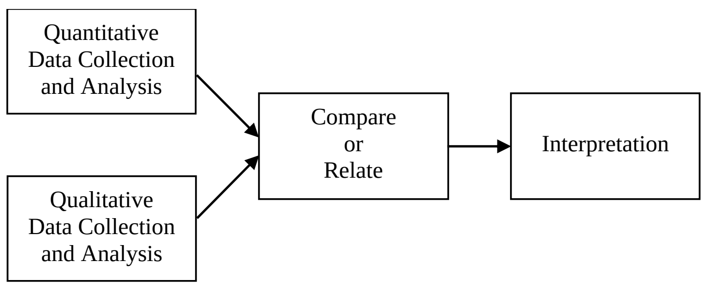

Figure 1. Convergent Parallel Mixed Methods Research Study

Participants

A directory of NZEB constructors and projects does not exist, therefore, the researchers first searched for literature on the NZEB construction projects in the United States from online sources, such as newbuildings.org, living-future.org, energy.gov, and usgbc.org. From the search, 21 completed NZEB projects were identified. Purposive sampling was then used to recruit industry professionals with NZEB project experience to participate in the study. The purposive sampling technique is the deliberate selection of a participant with particular characteristics or experiences, who will better be able to assist with the relevant research (Etikan, Musa, & Alkassim, 2016). For this study, the characteristic used was either residential or commercial NZEB project experience as a general contractor, subcontractor, project manager, estimator, architect, MEP engineer, energy consultant, sustainability consultant, project engineer, or project owner. In the search for participants with the appropriate experience, the assumption was made that if an individual did not have NZEB experience they would forward the request to a colleague who had NZEB experience within the organization. An email request to participate in the study was sent to 189 industry professionals, all of which had some role in the 21 NZEB projects identified through the online search of completed projects. The recruitment email explained the purpose of the study with a link to the Qualtrics™ survey questionnaire. A total of 27 completed surveys were received in a timeframe of 9 months. Five of the survey participants participated in the follow-up interviews. Seventy-four percent of the survey participants had industry experience of more than 20 years. Some of the participants mentioned more than one role on NZEB projects, which contributed in some part to the low number of participants given they had experience on more than one project. The demographic data for the participants is presented in Table 1.

Table 1

Participant Demographic Characteristics

Role on NZEB Projects	N
Energy Consultant	10
Project Manager	9
MEP Engineer	5
Architect	4
Owner	3
Owner's Representative	1
Estimator	1
Specialty Contractor/Subcontractor	1
Other (Sustainability Planner, NZE Coach, LEED Consultant, LBC Consultant, Design-Build Project Executive, Green Rater)	10

Data Collection and Analysis

The survey used for this study adapted a questionnaire previously developed for a 2013 study, *Project management knowledge and skills for green construction: Overcoming challenges* (Hwang & Ng, 2013). The questionnaire consisted of 24 questions, with 6 demographic related questions and 18 questions about the project management knowledge and skills needed to address the challenges of NZEB construction. A 5-point Likert scale was used for the questionnaire to measure participants' responses with a number between '1' to '5', where '1' indicated the lowest and '5' indicated the highest level of criticality. Numbers assigned to Likert-type items express a "greater than" relationship; however, how much greater is not implied. As the study had a series of individual questions that have Likert response options for the participants to answer, the analysis used mean *(M)* to measure central tendency, and standard deviation *(SD)* to measure dispersion. The responses were then numerically ranked based on their mean value. In the qualitative data collection, the semi-structured questionnaire was used that included three demographic questions, thirteen NZEB project management specific questions, followed up by additional probing questions, as necessary. All the qualitative data from the interview transcripts was input to MAXQDA, an analytical software, and further analyzed.

Results and Discussion

This section presents the results from the analysis of the quantitative and qualitative data collected for the study. In Table 2, the challenges that constructors face during NZEB construction project management are shown. In Table 3 and 4, the required knowledge and skills are listed. It is important to emphasize that although the list of challenges, knowledge areas and skills presented here are comprehensive, they are not exhaustive. Similar to traditional construction, the scope of challenges, knowledge areas and skills required for managing NZEB projects are also influenced by the context of the project.

The development of the requisite knowledge and skills has traditionally relied on academic degree programs that focus on delivering general construction content instead of specialty construction. To further develop knowledge and skills in the sustainable construction industry, professional constructors often rely on training and professional certification. Table 5 lists the categories of professional development most frequently pursued.

Table 2

Analysis Summary: Challenges

Category	*Challenge*	*M*	*SD*	*N*	*RW*	*RA*
Planning-related	Difficulty in comprehending the NZEB specifications in the contract details	3.00	1.02	27	1	9
	Planning of NZEB construction technique	2.96	0.79	27	2	10
	Planning of NZEB construction sequence	2.56	0.79	27	3	19
	Lengthy approval process for new green/NZEB technologies within the organization	2.52	1.00	27	4	21
	Adoption of different contract forms of project delivery	2.22	0.96	27	5	23
Project-related	Difficulty in the selection of subcontractors in providing NZEB construction service	3.04	0.92	27	1	8
	More alteration and variation with the design during the construction process	2.78	1.03	27	2	11
	More time is required to implement green/NZEB construction practices onsite	2.74	1.07	27	3	13
	Difficulty in assessing the progress of completion in NZEB Construction	2.19	0.94	27	4	24
Client-related	Level of risk the client is willing to take in Green/NZEB technologies	3.19	0.86	27	1	4
	Client uses a lot of time in making decision	3.07	0.86	27	2	6
	Special request from client pertaining to specified Green/NZEB technologies to be used	2.73	0.86	26	3	14
	Required date of completion	2.63	0.99	27	4	16
	Objective of the building project	2.52	0.92	27	5	21
Project team-related	Lack of communication among project team members	2.78	1.1	27	1	11
	Frequent meeting with green specialists	2.59	0.95	27	2	18
	Conflict with the architect over the type of material to be used	2.56	0.83	27	3	19
	Conflict of interest between consultant and project manager	2.19	1.06	27	4	24
	Green consultant’s delay in providing information	1.85	0.76	27	5	26
Labor-related	Workers’ unawareness of the correct methods and procedures	3.37	1.19	27	1	1
	Reluctance to change from traditional practices	3.33	1.15	27	2	2
	Lack of the technical skill regarding Green/NZEB technologies and techniques	3.30	1.18	27	3	3
Material and Equipment-related	High cost of green/NZEB material and equipment	3.11	0.74	27	1	5
	Uncertainty with green/NZEB material and equipment	3.07	0.94	27	2	6
	Decision on different green/NZEB material and equipment	2.73	0.90	26	3	14

Availability of green/NZEB material and equipment	2.63	0.82	27	4	16

In Table 2, challenges are organized into six categories: mean scores *(M)*, standard deviation *(SD)*, count *(N)*, ranks within *(RW)* and ranks across the categories *(RA)*. Based on the mean rank, the top three challenges faced by constructors executing NZEB construction projects are labor related. Workers' unawareness of the correct methods and procedures yielded the highest mean scores *(M=3.37)*, indicating that it is the most frequently encountered challenge. Reluctance to change from traditional practices was ranked second highest *(M=3.33)*, while lack of the technical skill regarding Green/NZEB technologies and techniques was third ranked challenge *(M=3.30)*.

The interview participants from this study verified that there is a tendency to revert to the old ways of doing things that people know and understand and have always done, whereas net zero energy building requires people to do things differently. One interview participant emphasized that the willingness to change is very critical, and people can learn better if they are not resistant to doing something different.

Workers' unawareness of the correct methods and procedures, and the lack of technical skills regarding green/NZEB technologies can be addressed by engaging contractors with knowledge on the environmental issues associated with construction activities and building materials during early stages of design. Forming interdisciplinary teams to work together throughout the project, increasing communication among team members, and implementing continuing professional develop training would be a good strategy in this regard. To address workers' reluctance to change from traditional practices, there must be a commitment to change the current mentality of employees. According to Shan, Liu, Hwang, and Lye (2020), senior management can have a major influence over their subordinates and the projects they are managing. Therefore, NZEB project managers should take an active role to raise the awareness of all employees about environmental issues, and knowledge about NZEB construction.

Table 3

Analysis Summary: Knowledge

Knowledge	*M*	*SD*	*N*	*Rank*
Cost Management	3.63	0.78	27	1
Schedule Management and Planning	3.63	0.82	27	1
Communication Management	3.63	0.87	27	1
Stakeholder Management	3.52	0.92	27	4
Materials Resource Management	3.30	0.81	27	5
Risk Management	3.15	0.89	27	6
Conflict and Dispute Management	2.85	0.93	27	7
Health and Safety Management	2.48	1.07	27	8
Claims Management	2.41	0.87	27	9
Human Resources Management	2.30	0.97	27	10

As shown in Table 3, the mean rank column indicates that there are three knowledge areas equally required for industry professionals to deal with the NZEB projects challenges. Those are cost management, schedule management and planning, and communication management *(M=3.63)*.

Communication management was cited as the most important knowledge by the interview participants. One interview participant emphasized communication as the key factor in the NZEB construction process. Another interview participant discussed various methods of coordinating team members so that everybody had frequent communications. NZEB projects require a more holistic and integrated approach where communication plays a critical role to achieve the project goal. Livesey (2016) verified that effective communication management plan needs to be in place for NZEB projects to facilitate collaboration in project teams, which also promotes active participation in decision making.

With regards to cost management knowledge, one interview participant emphasized understanding the relationship between the design decisions and their first cost implications compared to the cost over time as an important factor. When compared to conventional projects, green/NZEB projects tend to cost more to construct. Construction is a competitive industry dominated by price, therefore cost control is vital for contractors in the industry. A project manager’s competency with cost management has considerable impact on the success of projects. Project managers must manage and deliver the project within the budget constraint. Shan et al. (2020) stated it is essential to appoint a capable project manager that can lead the implementation of the green building practices on NZEB projects.

Table 4

Analysis Summary: Skills

Skills	*M*	*SD*	*N*	*Rank*
Teamwork	3.93	0.77	27	1
Leadership	3.81	0.72	27	2
Problem Solving	3.74	0.84	27	3
Decision Making	3.63	0.87	27	4
Analytical	3.33	0.77	27	5
Human Behavior	3.19	0.82	27	6
Delegation	3.11	0.79	27	7
Negotiation	3.04	0.88	27	8
Chairing Meetings	2.81	0.90	27	9
Presentation	2.78	0.87	27	10

From the mean rank of Table 4, teamwork was found to be the most important skill required to address the NZEB project challenges *(M=3.93)*, followed by leadership skills *(M=3.81)* and problem-solving skills *(M=3.74)*.

Interview participants cited teamwork as an important management skill essential for success working on NZEB projects. One interview participant mentioned teamwork as the core skill. Another interview participant said that rather than working in traditional silos where mechanical, electrical, et cetera, were just working by themselves, a series of interdisciplinary component teams work together throughout the entire NZEB project. Another interview participant emphasized the role of a leader in understanding and having skills at managing stakeholders, managing groups of people and figuring out what they really want from an NZEB building.

Teamwork can be facilitated by training, when both training and on-the-job experience play a positive role in enhancing problem solving skills. Leadership skills can be developed by both education and training. To enhance teamwork and performance outcomes, Salas et al. (2015) suggested some interventions, such as, conducting team cross-training and team building prior beginning the project.

Table 5

Analysis Summary: Professional Development

Professional Development	*M*	*SD*	*N*	*Rank*
On the job experience	4.00	0.61	27	1
Training	3.67	0.77	27	2
Education	3.48	0.63	27	3
Professional Certification	2.67	0.82	27	4

This study focused on the categories of professional development that industry professionals should acquire to manage NZEB projects effectively. These categories include academic background and experience-related knowledge as well as skills. Based on the mean rank of Table 5, on-the-job experience is the most effective mean of professional development *(M= 4.00)* to work in NZEB construction. Training was ranked second *(M=3.67),* followed by education *(M=3.48).*

The importance of training and on-the-job experience were discussed by the interview participants. One interview participant mentioned about the system of mentoring where less experienced people were assigned with more experienced to facilitate one-on-one mentoring. The role of seasoned professionals in providing the needed information or the one-on-one coaching needed for a specific individual was also mentioned. Regarding the role of education, one interview participant mentioned that a graduate should have the knowledge of designing energy efficient building, if not net zero.

Limitations and Future Research

Although the sample size of this study is considered small with only 27, insights about the knowledge and skills necessary for NZEB construction were revealed. More research is needed and a future study with a larger sample size should result in a higher response rate for individual items of the study and be more generalizable for industry practitioners and educators.

Most of the survey participants of this study mentioned more than one role on NZEB construction projects. Constructors in different roles may have a different set of challenges to overcome. The future research can limit the scope of selecting more than one role by the survey participants so that the researcher can compare project managers, designers, engineers, energy consultants, owners, and contractors' perceptions. Finally, participants who have both NZEB and conventional construction project management experience could be requested to rate their perceptions of knowledge and skills to respond to the project challenges in both NZEB and conventional buildings for a comparative analysis.

Conclusion

Managing construction projects is a challenging job due to the significant impacts of construction activities on the environment, economy, and surrounding community. Concerns over these impacts have spurred the need for green/NZEB buildings in the construction industry. Since constructors play an important role in the success of construction projects, it is essential to identify the critical knowledge and skills that constructors require to deal with the challenges of NZEB construction project. The objectives of this study were to identify the knowledge areas and skills required to be a competent constructor of NZEB construction projects, and to summarize the relative importance of the various mechanisms for professional development.

The analysis of the responses from the survey revealed knowledge areas and skills that are essential to respond to the challenges. The most important challenges were workers' unawareness of the correct methods and procedures, reluctance to change from traditional practices, and lack of the technical skill regarding Green/NZEB technologies. The most important knowledge areas were cost management, schedule management and planning, and communication management. The most important skills required to mitigate the challenges are teamwork, leadership, and problem-solving skills. The contribution of academic education to the competency of NZEB constructors was rated lower than that of formal industry training attended provided by employers. Similarly, the perceived contribution of industry training was outranked by that of experiences on the job site.

Based on the results from this study, it is evident that further development of competencies for NZEB construction is needed, both in higher education and in the construction industry. This research, therefore, advocates for a greater level of NZEB content in construction education and training programs. Collaboration with industry professionals who have NZEB project experience would provide a resource for knowledge and skill development.

References

Dogbegah, R., Owusu-Manu, D., & Omoteso, K. (2011). A principal component analysis of project management competencies for the Ghanaian construction industry. *Australasian Journal of Construction Economics and Building, The*, *11*(1), 26-40.

Edum-Fotwe, F. T., & McCaffer, R. (2000). Developing project management competency: perspectives from the construction industry. *International journal of project management*, *18*(2), 111-124.

EPA (2021). Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2019. Retrieved November 14, 2021, from https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2019

Etikan, I., Musa, S. A., & Alkassim, R. S. (2016). Comparison of convenience sampling and purposive sampling. *American journal of theoretical and applied statistics*, *5*(1), 1-4.

Hwang, B. G., & Ng, W. J. (2013). Project management knowledge and skills for green construction: Overcoming challenges. *International journal of project management*, *31*(2), 272-284.

Livesey, P. V. (2016). Insights of project managers into the problems in project management. Construction Economics and Building, 16(1), 90-103.

Marcelino-Sádaba, S., González-Jaen, L. F., & Pérez-Ezcurdia, A. (2015). Using project management as a way to sustainability. From a comprehensive review to a framework definition. *Journal of cleaner production*, *99*, 1-16.

PMBOK. (2017). *A guide to the Project Management Body of Knowledge: (Pmbok Guide)*.

Salas, E., Shuffler, M. L., Thayer, A. L., Bedwell, W. L., & Lazzara, E. H. (2015). Understanding and improving teamwork in organizations: A scientifically based practical guide. Human resource management, 54(4), 599-622.

Shan, M., Liu, W. Q., Hwang, B. G., & Lye, J. M. (2020). Critical success factors for small contractors to conduct green building construction projects in Singapore: identification and comparison with large contractors. Environmental Science and Pollution Research, 27(8), 8310-8322.

U.S. Green Building Council. (2014). *Leed Core Concepts Guide: An introduction to Leed and Green Building*.

SUBMISSION: 35

TITLE: Using technology as a learning tool: a literature review of ways in which technology can benefit and hinder learning outcomes

Reviewer Comments Summary Sheet

Comment	Reviewer #	RUBRIC SECTION: Comment	Addressed? Y/N	Response
A	1	FORMATTING: Please ensure that within text references are made in accordance with the required format.	Y	One in text citation was updated with a date that was a pre-print, and a handful of full references at the end of the paper have been revised. We are not sure what else reference-wise needs to be revised according to the template if we could get pointed corrections.
B	1	CONTRIBUTION: Only to some extent. Conclusion can be much informative and present key findings. Could have stated future research directions.	Y	Further research suggestions have been added to the conclusions.
C	1	TITLE, ABSTRACT, KEYWORDS: Abstract need to be more informative. Add main findings. Suggest adding learning technology as a keyword.	Y	Further information has been added to the abstract. Learning technology has been added as a keyword.
D	1	METHODOLOGY: Require more details regarding the process adopted for the literature review. 1. What were the sources used in accessing literature? e.g.: manual library access, google scholar, any journal databases etc. 2. What were the keywords used in searching? 3. Was a specific time span used? 4. What was the overall approach? e.g.: A systematic review, thematic review etc.	Y	More details about how literature was searched, including databases and key terms, time frames, and the thematic approach to literature analysis.
E	1	FIGRES/TABLES: No tables or figures used. A table or a diagram can improve the readability / presentation of the paper.	N	No figure was made for this research, and we were concerned about page count and merit of adding a figure.
F	1	OVERALL: A timely and worthwhile topic investigated. Suggest addressing the comments above prior to acceptance.	Y	Thank you for your comments. We appreciate your feedback. All of the comments have been addressed to the best of our ability.
G	2	CONTRIBUTION: The biggest issue with this literature review is that it presents itself as a look at "recent shifts" in student learning, but 2/3 of the citations are from papers that are 5 or more years old. There is a lot of current research (many published in the ASC proceedings and ASC journal) that discuss student learning in construction.	Y	More modern literature has been added or swapped for older sources to update the mass age of citations.
H	2	LITERATURE REVIEW: Paper needs to address more current look at the literature on student learning	Y	More modern literature has been added or swapped for older sources to update the mass age of citations.
I	2	METHODOLOGY: The methodology for how the literature review was conducted is vague. Consider what keywords were searched, how the decisions were made to include and exclude certain articles, etc.	Y	More details about how literature was searched, including databases and key terms, time frames, and the thematic approach to literature analysis.

Using technology as a learning tool: a literature review of ways in which technology can benefit and hinder learning outcomes

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To enhance learning outcomes, and to deal with recent shifts in distance learning, instructors are constantly challenged to create more engaging educational content, increasingly so through online platforms. Gaps in how technology is viewed and utilized can cause frustrations in the classroom. Traditional teaching has focused on visual, auditory, and kinesthetic learning styles (VAK); however, these methods are no longer meeting the dynamic engagement needs of students in higher education. Technology in the classroom has changed the way students and professors interact with the material presented, and educators have more ways than ever to adapt and improve communication of the material through learning management systems (LMS). This paper presents ways that higher-education instructors can create learning environments to foster understanding and curiosity, strategies to help students learn, and ways to bridge technological gaps in construction and architecture education. Through aa thematic literature review, this paper explores teaching and learning styles, strategies to help students, and differences between classroom and online learning. Findings from this review suggest the advances in technology for the classroom are changing the classroom landscape, including how in-class time can be spent, communication, assignment and assessment design, and the availability of resources for students.

Key Words: construction education; technology; learning styles; pedagogy; learning technology

Introduction

The digital age has shifted the way our society works and with it how the classroom landscape functions. To enhance learning outcomes, instructors are having to create more engaging content and provide new ways of learning to utilize the advantages that modern technology can offer (Gu et al., 2013). Higher-education instructors are working to create learning environments that foster understanding and curiosity, develop strategies to help students learn, and beginning to bridge technological gaps. Especially in design and construction classes, technology is challenging the way students and professors interact with the material presented, and educators have more ways than ever to adapt and improve communication of their material (Harasim, 2011).

This paper examines research surrounding how technology and other factors are changing the ways students are learning in the classroom, especially in the design and construction disciplines where so many of the students are visual and hands-on learners (Day, 2015; Day & Orthel, 2015). The literature review begins by describing the various ways students learn and how their learning style is affected by a multitude of factors. How students learn can be a determining factor when introducing technology into a classroom. The next section explores different ways teachers can better understand their students and the relationships they have with them, making sure the technology introduced is helping students in the most effective ways. Finally, the studies presented describe the ways students are using technology both in and out of the classroom and how technology use can impact students, some ways being detrimental, and some being beneficial. Then, in the final discussion, comparisons between the studies examine evidence to support or refute the claims that learning through online platforms as seen through the SARS-COVID 19 pandemic, requires different teaching and learning styles compared to in person learning.

Methodology

This thematic pedagogical literature review was developed to investigate the variables that affect learning, specifically how technology has shaped the higher education classroom. The literature gathered for this review includes peer-reviewed journal articles and books from the academic, teaching, and technology fields, gathered to identify common topics, trends, and significant scholarly work. Peer-reviewed articles and well-recognized reviews were analyzed and organized into their related topics to make the collective information organized for reading. Additional articles, sourced from significant pieces of literature, led to further discoveries, and bolstered the content provided from multiple angles. Literature was searched through science direct, the researcher's university library system, and google scholar, using key terms such as learning styles, pedagogy, teaching technologies, construction education, student attention, adult learning, and academic impacts of pandemic. Portions of this literature review were narrowed to references published in the last 10 years, but significant research published before this date was included to provide historical context and comparisons of how approaches to teaching and learning have changed over time. Literature was gathered and analyzed to answer to the following leading research questions: *R1: How are students in higher education settings learning with the introduction of technology in the classroom? R2: How is technology changing the classroom landscape in the design and construction disciplines?* The following section highlights three key topics: how students learn, student relationships with their peers and instructors, and technology use in and out of the classroom. Each section of this literature review discusses the background of each respective theory and how it is relevant to digital teaching and the future of technology in the classroom.

Literature Review

Technology can be used as a useful learning tool in the classroom, but it can also be misused and distract from the learning experience. When learning about building science, for instance, or how buildings are built and operated, technology and the opportunities it provides are exceptionally helpful. For example, the digitization of the design and construction process provides opportunities for students in these disciplines to better understand the interdisciplinary nature of the construction process. The existing research on technology in the classroom primarily caters to how different students learn with technology-centric methods; however, it is also important to know how students best learn naturally. This thematic pedagogical literature review will investigate how technology and learning styles have changed in recent years and how educators are working to change their content delivery.

How Students Learn

Learning Styles are particularly important in understanding how technology can be best used to help students and educators create powerful learning environments. Learning Styles, or characteristics of how students absorb, process, and comprehend the information given to them, have previously been discussed by design and construction educators as a way to better understand their students, and cater their materials to help them understand spatial design problems (Mostafa & Mostafa, 2010). One popular theory adopts the idea that there are three main types of learners. The VAK method includes Visual Learners, Auditory Learners, and Kinesthetic Learners (Fleming & Mills, 1992). Understanding how people learn can change the way that educators teach their lessons (Price, 1983; Ralston et al., 1978). In design and construction education, a vast majority of students are visual learners who benefit from spatial and active learning methods (Mostafa & Mostafa, 2010). It is critical for design and construction instructors to understand the differing types of learners in their classroom to blend teaching material, tactics, and technology in ways that help the students best learn; often a mix of methods is required to achieve learning.

Coleman, Rourke, and Allen (Coleman et al., 2011) found that it is important to teach students in the way they learn best, which may seem obvious, but this may be overlooked by instructors as they try to get through course learning objectives as efficiently as possible. By providing instructional content to design and construction students through visual methods, a richer and more well-rounded education can be facilitated. Visual learning methods provide students with a better understanding of the "big picture" while providing multiple opportunities to learn the content (Coleman et al., 2011). Researchers also agree the way you show information to visual learners is crucial (Chen, 2020; Ibrahim & Kadiri, 2018; Knowles, 1990; Mayer & Massa, 2003). It is difficult to cater to different learning styles, especially in classes with over fifty students. Coleman et al. (Coleman et al., 2011) explores the way classrooms could work if they were set up to respond to student's visual inclinations as if they were experiencing the materials in "the real world." If colleagues could collaborate on their assignments and play to each other's strengths, each student would feel more confident in their part of the project, giving more confidence to the subject.

Understanding how people learn is especially important when selecting what technology will help students learn. The National Research Council (Council, 2000) examined how people learn by asking how to make student's ideas visible through a 2-year study conducted by the Committee on Developments in the Science of Learning , so that educators could see the ways students were learning in different environments. This is called the transfer of learning, which relates to how students can gather information, process it in their minds, and then relay it back to others. The conclusions found the importance of having a goal of learning to understand, as opposed to simply memorizing, had the greatest success in the transfer of learning. Similar to findings from Coleman et al. (Coleman et al., 2011), conclusions also highlighted that people learned best when they could apply their developed skills to help them in real-life situations. Furthermore, in higher education, learning occurs through in classroom and out of classroom activities, including online instruction, digital tools, through engagement activities or in-person projects. However, instructors may not understand the amount of time it takes for students to learn what has been taught, and students may not feel motivation to dedicate time to different modalities of teaching if they do not understand the benefit or the graded impacts of their work (Coffey & Clarke, 2021).

Students often learn and process in the same ways professionals learn in industry and professional practice (Li, 2019). Designers, for instance, are known for their ability to solve problems and using their creative skills and by the iterative process of design itself (Day & Orthel, 2015). In a study by Pavel (Pavel, 2017) about the ways designers learn, the analysis showed designers learn best through visual stimulation. The primary way designers in this study communicated their knowledge was through visual applications. The study also looked at how different “visual objects of representation” meaning what tools were given to help the participants solve the problem and how they shaped the way the problem was solved by two diverse groups of designers. The participants were Masters of Arts design students, and the two groups were given the same objective, each with separate ways they were expected to deliver their ideas to the stakeholders. One group was given the materials and a direction to focus on to convey the solution to the problem, and the other group was given no guidance as to how they would need to communicate their solution. The group that was given direction and materials to use produced more creative and well-developed ideas. This small amount of direction helped the designers focus their energy on how to develop the best solution instead of spending wasted time trying to work out what to show for the solution. This study shows that when given expectations or ability to visualize what the outcome should be, students perform better. This finding is relevant to the format in which professors and instructors can design assignments and their expectations for the students to be successful.

Many studies that evaluate how students learn utilize question and answer formats to gain the needed information, studies that rely on participants reflection or observation throughout the study and how they learned through a given time period or type of teaching. Modern technology has made it possible to get quantitative as well as qualitative data about this topic. There have been several studies that correlate interest in a subject with a student’s concentration and achievement. In a study at Jiangsu Normal University (Yang et al., 2013), researchers found there were strong correlations between interest and concentration during a presentation as well as between concentration and achievement. In another study, Yang, Li, and Lu (Yang et al., 2015) found mobile learning (on a cell phone) did not have a significant difference in the level of concentration from learning from a computer. The biggest factor in the concentration level of the student was how interested they were in the subject. In their study, they used “m-learning” as a term to describe mobile learning, which can be from a computer, tablet, or phone. They researched three types of m-learning: mobile learning, video-based, graphical, and text-based media and discovered differences in how forms of media affect student attention. They found it was important for instructors to know and understand how interested the students were in the subject because the type of media the instructor may need to vary if the student has a high, medium, or low interest. For instance, if a video is extremely in-depth about a concept, the more interested student may feel the amount of information is superfluous. However, when showing the same video to students with a moderate or low interest in the subject, the amount of information will pique their interest.

Technology can help decrease the amount of time spent on coordinating group projects, improving communication between members with ease. Colbeck, Campbell, and Bjorklund (Colbeck et al., 2000) studied how students felt about group projects, and the authors found that students appreciated the interactive learning experiences they received from group work. Further, a newer study found that project-based teaching (PBT) may enhance student interest in subject matter when course objectives and the connection to subject materials are well explained to students, (Gunawan et al., 2022). These studies align with findings from Bransford et al. (2005) who found that students who worked together through class projects and learned from each other’s insights were better able to convey their thoughts to others. Many employers value the ability for their employees to work with teams and in collaborative environments, however, entry-level students may not understand the relevancy and real-world applications of the delivered content through lectures alone and require group-based activities to commit knowledge to skills. Applying social constructivist approaches to learning, such as relating in-class taught concepts to a group project, can greatly improve the learning outcomes of early-career construction students and their success when entering the industry (Brittle, 2021). If the technology being used is not a traditional platform, students will have to use additional cognitive function in order to understand the program which will diminish their abilities to learn the intended material. By using widely adopted technology platforms for group-work, the negative aspects of these collaborative projects can be diminished. Through the SARS-COVID 19 pandemic the use of technology has shot forward because of remote learning, this change in the way curriculum is delivered has shifted the ways that instructors can connect with their students, but the more comfortable students and teachers alike become with the platforms they are using the focus on understanding technology shifts to again focus on fostering the relationships that are created in the classroom. Technology can be used to enhance the student learning experience in many ways as mentioned above, diversifying the student experience. Tools such as social media, virtual reality tools, and video viewing platforms can also be used to enhance the student-teacher relationship, improve student soft skills, and increased student engagement (Lucas & Gajjar, 2020). As students are more frequently requesting communication between their colleagues and instructors, various programs, and websites such as Microsoft Teams, Google Drive, and learning platforms like Blackboard, Google Classroom and Canvas help facilitate stronger communication networks than previously available in face-to-face only education models. However, it is important to remember that direct communication with students, clear instructions and expectations, as well as technical support and training on using these platforms is essential to student success in a virtual or flipped classroom setting, as seen through the lasting impacts of the pandemic (Camilleri & Camilleri, 2022). Access to feedback and clarification from instructors has become an integral part of the student-teacher relationship and can be facilitated through these platforms.

Technology in and out of the classroom

The world of education has changed dramatically in the past decade (and especially in the past year of facing a pandemic and virtual learning). As such, the use of mobile technology in everyday life has become the norm (Fidishun, n.d.; McWhirter & Shealy, 2020). Some researchers feel the amount of technology present in the lives of students today is simply a hindrance to education (Naomi, 2015). Others feel technology can facilitate deeper learning and provide new and unique experiences that may not be possible without the access to technology (Lloyd, 2000; Miller, 2014). Since these articles have been written, technology is the virtual classroom has been come a required way of life as students and instructors alike must work from home (i.e., in 2020, 2021) due to the impacts of COVID-19. In a flipped classroom model, students are more responsible for their learning through asynchronous materials outside of class, with more active in-classroom learning strategies (McWhirter & Shealy, 2020). There is still much to learn about how this work from home model and heavy use of technology has impacted overall learning outcomes, but is a promising strategy for construction engineering and management (CEM) education (Lee & Kim, 2021). This next section discusses the implications that technology has on students beyond the classroom, benefits and potential downfalls of using technology, and how the gaps are bridged in instructional settings.

Zhang, Russo, and Fallon, (Zhang et al., 2015) conducted a study to see if there was a correlation between college students' stress levels and their use of technology. They found that students who had self-imposed boundaries with technology, meaning they self-moderated their time, use, and reliance on technologies, experienced less stress from technology in their lives. While there are many positives to active use of technology in the classroom, this study found students also wanted to ask instructors to think about the need for technology for projects before assigning it. It is critical for students and instructors to be conscious of the amount of communication and information given to be within reasonable timeframes. While the connectivity granted through educational technology has benefits, instructors must also consider how over-connectivity can be overwhelming (Zhang et al., 2015).

Constant need to be connected for the sake of checking emails or deadlines has the ability to negatively affect student success and focus, and this study recommends that instructors first determine their students' comfort levels using technology in educational settings and set clear boundaries and expectations for communications via technology early in a course. This method can also be beneficial in preventing burnout on the instructor's end as well.

McDaniel (McDaniel & Drouin, 2019) studied the effects of technology, or "technoference," and our ability to focus on what is in front of us. This research studied interpersonal relationships as well as the difficulty students had focusing on the material when technology use increased. Since many students are so closely attached to their technology, it can seem that technology is more important than the person in front of them, which can diminish social relationships, communication, and learning. His study found "technoference," when looked at through a social exchange model, provided a lens to examine the negative effects of technology of interpersonal relationships. The term McDaniel used to describe this type of distraction was called "phubbing;" phubbing is a combination of "phone" and "snubbing," which has been observed and studied by other researchers as a way to understand technological impacts on social interactions (Chotpitayasunondh & Douglas, 2016, 2018). When this concept is applied to the classroom, students on their phone may not be paying attention to the instructor, or the material being covered, often too immersed in another virtual setting. This does not create a healthy learning environment for the student nor the educator as the students are not learning to their fullest potential, and the educator does not feel respected, which may translate to having a more difficult time teaching the material effectively. This creates a negative association with technology for many instructors due to clear hindrances to the learning environment. If the context and use of technology in classrooms is changed, technology can become a tool providing them with the information they need to learn and be a positive aspect of the learning environment. In relationships of any kind, people want to feel that their time and effort is respected; when students are distracted, this can increase the feeling of disrespect in others in the learning environment, as well as for the instructor. If technology is not used in a conscious way, it can often lead to distraction and increased feelings of disrespect for those involved.

Technology Building Science and Construction Courses

Students learning building science or other design or construction-related topics, as mentioned before, benefit greatly from seeing what they are learning, as well as having the ability to apply their knowledge to solving problems. This can be made possible by traditional slide-deck visual formats and dynamic presentations, as well as through experiential learning formats, such as field trips and the creation of physical models and diagrams. Shaffer et. al. (Shaffer et al., 2015) studied how the use of technology in the classroom is helping educators better cater to individual students. Through his methods, he delivers course content entirely digitally, allowing students to receive content on their own terms and find activities that allow them to practice their skills on their own. He believes there are three main ways students can learn digitally: through digital workbooks, digital readings, and digital internships to simulate real-world practice. Digital workbooks simply digitized worksheets, like paper handouts, that are delivered through online learning platforms. Digital readings are similar in nature, allowing students the ability to virtually take notes, while allowing instructors the ability to track progress and prompt students throughout a reading. Reaching students beyond the traditional classroom space, digital internships can help students feel like they are in practice and learn how to think about real-world problem solving without having the attached risks and commitments. Experiential learning helps students to understand more deeply their subject matter with potential of applying and testing skills developed in the classroom (Collins & Redden, 2021). Transforming class settings that have associated "lab" time integrated into the course content, digital internships and workshops provide the opportunity for students to apply what they have learned and apply those skills to specialized projects. Field trips and other traveling opportunities become harder to coordinate as class sizes grow. Creating digital experiences, such as virtual building tours or field trips, can replicate what you would learn in real life without the extra hassle or the often-extra cost. Shaffer found that technology can help create experiential learning opportunities while keeping the amount of time to prepare lessons and teach them similar to the time it would take to create a traditional lesson (Shaffer et al., 2015). Through the COVID-19 pandemic, these digital experiences have become the sole source of experiential learning opportunities.

In recent years, following the shift in industry to use of technology and digital models to expand the potential and detail of projects, a shift in skills taught to students must reflect needs from professionals in the work force. Integration of Building Information Modelling or “BIM” into coursework is a successful way to teach students practical technologies that they will use in practice, and it also enforces the technological adaptability that students need to comprehend complex systems and problems (Lorek, 2018; Noble & Kensek, 2014; Yan et al., 2011). Many design schools and studios are adopting digital methods of communication and documentation, encouraging students to familiarize themselves with emerging technology prior to entering the workforce.

Technology can create many positive opportunities in educational settings, but it is also important for students to have face to face interactions with their instructors and peers as well to meet their needs. In a study done in 2021 about students with high functioning autism, Reicher found that while many students are enjoying their school days from home, and some are even excelling with the online academic curriculum, they are struggling with the “hidden curriculum” students learn in face-to-face formats, which include learning societal and communication skills, traditionally learned through interactions with their peers (Reicher, 2021). While learning from home during the pandemic is benefitting many students (it should be noted that the opposite is also true for some students), extended periods without social interaction can hinder students’ communication and ability to navigate life beyond school.

One of, if not the most difficult aspect of technology use in the classroom, is understanding when and how to use technology to best teach and transfer knowledge. Huffman and Huffman (Huffman & Huffman, 2012) studied how different external factors impacted students' effective use of technology and how students were expected to use technology against their actual performance in the class, if the students don't understand the technology, even if they understand the content, they will not be able to demonstrate they understand the content because they aren't able to correctly use the technology. The study found that students who felt there was a need for technology used it more, and further, those who felt technology was needed were more intentional with their technology use. Their study also found when a professor deemed technology necessary to use on a project, students were more likely to use the technology in an appropriate and useful way. This finding is significant, as student inclination to using technology in the classroom must be focused and clearly defined for their success.

Technology is developing rapidly, and college students of this digital generation using these technologies in everyday life. Lai and Hong (Lai & Hong, 2015) discussed the change in how students in university classrooms today have a very different style of learning than their parents. “Digital natives” is the term used to describe these students, and this study observed university students to determine if the term was indeed accurate. They found that most of the participants were digitally literate, however, they did not want digital technologies in every aspect of their learning. For example, many participants in the study noted that they preferred to do group work in person, as opposed to doing the work via technology, as communication between group members can be challenging (this is further supported by findings in previous sections of this literature review). The other major finding of this study was that even though technology has created a culture that likes immediate gratification and instant access to data, these students had moderate expectations for immediacy in their education. This finding, supported by other studies, means that even though there are many parts of the students' lives that are filled with immediate answers, the learning environment does not need to be one of them (Lai & Hong, 2015; Shtepura, 2018). The idea that learning can take time, the answers are not always obvious, and care is needed to process and select the best answer in fostering critical thinking skills. Learning should be creative, interactive for students and their peers, as well as autonomous, meaning that they can learn through their devices intuitively. The prevalence of technology in modern students' lives has formed their skillsets and the ability to use technology to their advantage both in the classroom and through the rest of their lives.

Conclusions

To briefly sum up the findings of this body of research, the attention spans, and ways in which students are learning today is changing rapidly, in the past year with the restrictions from SARS-COVID 19 has changed the way that students are able to learn. Findings from this review suggest differences in how students learn is complicated but can be better understood by understanding how those students best learn on a class-by-class basis; for instance, providing a learning style quiz at the beginning of a semester or quarter may help inform instructors for how to best deliver materials, design the learning management system for best use, and improve learning outcomes. Research also suggests educators and students alike need to find common ground and learn from each other to create a more enjoyable learning environment for all. While the principles of learning have not changed drastically, the purpose of this paper is to help instructors improve the delivery and information students need to succeed, that are constantly changing as students and the world shift to different modalities of learning and teaching. Students still like to see what they are learning (and what is expected of them) written down, whether in physical form or virtually through presentations and reference documents, and clearly communicated in a consistent manner. Students want to know how projects, both solo and group projects, connect to their expected learning outcomes and the time commitment before starting the work, and need the ability to ask questions, suggesting flipped classroom strategies or hybrid methods of teaching construction students may benefit learning.

The educational approach has surely changed in the last few years, and the world of education is different too. All the changes that came about out of necessity due to the SARS-COVID 19 pandemic have proven that technology can be a great benefit and teaching tool for some students. While the world is shifting back towards a mostly "normal" state, these digitally accessible methods of using technology are going to continue to prove themselves a useful tool for students and educators alike. Technology has changed the classroom landscape drastically, but the backbone of education is not technology, it is learning, and technology can be used as a tool to assist that process drastically. Future research should further explore the connection between learning and technology in and out of the classroom. It will be even more critical as learning modalities change after the COVID-19 pandemic, and continue to evolve, to ensure students are using tools in the classroom that help them best learn for architecture and construction disciplines.

References

Bransford, J. D., Barron, B., Pea, R. D., Meltzoff, A., Kuhl, P., Bell, P., . . . Sabelli, N. H. (2005). Foundations and opportunities for an interdisciplinary science of learning. In P. Alexander & P. Winne (Eds.), *The Cambridge handbook of educational psychology* (2 ed., pp. 209-244). Cambridge University Press. https://doi.org/10.1017/CBO9780511816833.003

Brittle, P. (2021). Improving Student Learning in an Entry Level Construction Management Course Through the Application of a Social Constructivist Approach to Teaching. ASC 2021. 57th Annual Associated Schools of Construction International Conference,

Camilleri, M. A., & Camilleri, A. C. (2022). The Acceptance of Learning Management Systems and Video Conferencing Technologies: Lessons Learned from COVID-19. *Technology, Knowledge and Learning*, *27*(4), 1311-1333. https://doi.org/10.1007/s10758-021-09561-y

Chen, G. (2020). A visual learning analytics (VLA) approach to video-based teacher professional development: Impact on teachers' beliefs, self-efficacy, and classroom talk practice. *Computers and education*, *144*, 103670. https://doi.org/10.1016/j.compedu.2019.103670

Chotpitayasunondh, V., & Douglas, K. M. (2016). How "phubbing" becomes the norm: The antecedents and consequences of snubbing via smartphone. *Computers in human behavior*, *63*, 9-18. https://doi.org/10.1016/j.chb.2016.05.018

Chotpitayasunondh, V., & Douglas, K. M. (2018). The effects of "phubbing" on social interaction. *Journal of applied social psychology*, *48*(6), 304-316. https://doi.org/10.1111/jasp.12506

Coffey, R., & Clarke, S. (2021, June 9, 2021). Construction Management Teaching Methods and Assignments: Perception versus Reality. ASC 2021. 57th Annual Associated Schools of Construction International Conference, Virtual.

Colbeck, C. L., Campbell, S. E., & Bjorklund, S. A. (2000). Grouping in the Dark: What College Students Learn from Group Projects. *The Journal of Higher Education*, *71*(1), 60-83. https://doi.org/10.2307/2649282

Coleman, K., Rourke, A., & Allen, B. (2011). Actively Engaging Visual Learner's Online. *International Journal of Technology, Knowledge and Society*, *7*(5), 127-142. https://doi.org/10.18848/1832-3669/CGP/v07i05/56232

Collins, W., & Redden, L. (2021). Improving Student's Estimating Abilities through Experiential Learning. *International Journal of Construction Education and Research*, *17*(2), 117-132. https://doi.org/10.1080/15578771.2020.1739178

Council, N. R. (2000). *How People Learn: Brain, Mind, Experience, and School: Expanded Edition*. The National Academies Press. https://doi.org/doi:10.17226/9853

Fidishun, D. (n.d.). Andragogy and technology: Integrating adult learning theory as we teach with technology. In P. S. G. V. School (Ed.), (Unpublished Manuscript ed.). Malvern, PA: Graduate Professional Studies, Penn State Great Valley School.

Fleming, N. D., & Mills, C. (1992). Not another inventory, rather a catalyst for reflection. *To Improve the Academy*, *11*, 137.

Gu, X., Zhu, Y., & Guo, X. (2013). Meeting the "Digital Natives": Understanding the Acceptance of Technology in Classrooms. *Educational technology & society*, *16*(1), 392-402.

Gunawan, T. J., Wang, J., & Liao, P.-C. (2022). Factors of Project-Based Teaching That Enhance Learning Interest: Evidence from Construction Contract Management Course. *Sustainability*, *14*(22), 15314.

Harasim, L. (2011). *Learning Theory and Online Technology : How New Technologies Transform Learning*. Hoboken : Taylor & Francis.

Huffman, W. H., & Huffman, A. H. (2012). Beyond basic study skills: The use of technology for success in college. *Computers in Human Behavior*, *28*(2), 583-590. https://doi.org/10.1016/j.chb.2011.11.004

Ibrahim, A. A., & Kadiri, G. C. (2018). Integrating Mobile Phones in Teaching Auditory and Visual Learners in an English Classroom. *English Language Teaching*, *11*(12), 1. https://doi.org/10.5539/elt.v11n12p1

Knowles, M. S. (1990). *The adult learner : a neglected species* (4th ed. ed.). Houston : Gulf Pub. Co.

Lai, K.-W., & Hong, K.-S. (2015). Technology use and learning characteristics of students in higher education: Do generational differences exist?(Report). *46*(4), 725. https://doi.org/10.1111/bjet.12161

Lee, N., & Kim, S. (2021). Exploring the Flipped Classroom Model in Construction Engineering and Management Education: A Case Study. ASC 2021. 57th Annual Associated Schools of Construction International Conference,

Li, Y. (2019). Design and Design Thinking in STEM Education. In A. A. d. Alan H. Schoenfeld, Arthur C. Graesser, Lisa C. Benson, Lyn D. English & Richard A. Duschl (Ed.). <*i data-test="journal-title" style*="box-sizing: inherit;">Journal for STEM Education Research

Lloyd, L. (2000). *Teaching with technology : rethinking tradition*. Medford, N.J. : Information Today.

Lorek, S. (2018). *What is BIM? (Building Information Modeling)*. Trimble. Retrieved 4/30/2020

from https://constructible.trimble.com/construction-industry/what-is-bim-building-information-modeling

Lucas, J., & Gajjar, D. (2020). Effects of Virtual Reality on Student Learning in Materials and Methods Course. ASC 2020. 56th Annual Associated Schools of Construction International Conference,

Mayer, R. E., & Massa, L. J. (2003). Three Facets of Visual and Verbal Learners: Cognitive Ability, Cognitive Style, and Learning Preference. *Journal of Educational Psychology*, *95*(4), 833-846. https://doi.org/10.1037/0022-0663.95.4.833

McDaniel, B. T., & Drouin, M. (2019). Daily technology interruptions and emotional and relational well-being. *Computers in Human Behavior*, *99*, 1-8. https://doi.org/10.1016/j.chb.2019.04.027

McWhirter, N., & Shealy, T. (2020). Case-based flipped classroom approach to teach sustainable infrastructure and decision-making. *International Journal of Construction Education and Research*, *16*(1), 3-23. https://doi.org/10.1080/15578771.2018.1487892

Miller, M. D. (2014). *Minds Online: Teaching Effectively with Technology*. Cambridge: Harvard University Press.

Mostafa, M., & Mostafa, H. M. H. (2010). How do architects think? Learning styles and architectural education. *ArchNet-IJAR*, *4*(2/3), 310-317. https://doi.org/10.26687/archnet-ijar.v4i2/3.139

Naomi, S. B. (2015). *Words Onscreen: The Fate of Reading in a Digital World*. US: Oxford University Press.

Noble, D., & Kensek, K. M. (2014). *Building information modeling : BIM in current and future practice*. John Wiley & Sons.

Pavel, N. (2017, 7 & 8 September 2017). How designers learn: Objects of representation as means of knowledge transfer. 19th Annual International Conference on Engineering and Product Design Education, Oslo, Norway.

Price, G. E. (1983). Diagnosing learning styles. *New Directions for Adult and Continuing Education*, *1983*(19), 49-55. https://doi.org/10.1002/ace.36719831907

Ralston, Y., Education, E. C. o. H., National Institute of, E., & Claxton, C. S. (1978). *Learning styles : their impact on teaching and administration*. Washington : American Association for Higher Education.

Shaffer, D., Nash, P., & Ruis, A. (2015). Technology and the New Professionalization of Teaching. In (Vol. 117, pp. 1). New York: Blackwell Publishing Ltd.

Shtepura, A. (2018). The Impact of Digital Technology on Digital Natives' Learning: American Outlook. *Comparative Professional Pedagogy*, *8*(2), 128-133. https://doi.org/10.2478/rpp-2018-0029

Yan, W., Culp, C., & Graf, R. (2011). Integrating BIM and gaming for real-time interactive architectural visualization. *Automation in Construction*, *20*(4), 446-458. https://doi.org/10.1016/j.autcon.2010.11.013

Yang, F.-Y., Chang, C.-Y., Chien, W.-R., Chien, Y.-T., & Tseng, Y.-H. (2013). Tracking learners' visual attention during a multimedia presentation in a real classroom. *Computers & Education*, *62*(C), 208-220. https://doi.org/10.1016/j.compedu.2012.10.009

Yang, X., Li, X., & Lu, T. (2015). Using mobile phones in college classroom settings: Effects of presentation mode and interest on concentration and achievement. *Computers & Education*, *88*, 292-302. https://doi.org/10.1016/j.compedu.2015.06.007

Zhang, J., Russo, T. J., & Fallon, M. A. (2015). Impact of Technology Devices on College Students' Stress Levels of Using Technology. *International Journal of Technology in Teaching and Learning*, *11*(2), 90.

Analysis of Current BIM Execution Plans and Contract Documents to Support Automation of Clash Resolution

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Step one of MEP coordination process identifies the clash between MEP elements followed by step two identifying their potential resolution. Clash identification has been automated using software like Navisworks yet clash resolution remains a slow and manual process. Use of Machine Learning has been explored by researchers to automate clash resolution. These researches utilize graphical information and attributes embedded into Building Information Model (BIM) elements to develop a Machine Learning model making BIMs an integral part of the automation. The literature review shows that the successful implementation of BIMs is supported by well-executed BIM Execution Plans (BxP) and Standards. Therefore, it can be said that a successful implementation of clash resolution automation will require the support of these documents. To assess the readiness of BxP to support the automation of clash resolution, the authors in this paper reviewed three BxP and Standard guides. A comparative analysis of three industry standard BxP and Standard guides was conducted to reveal the topic covered by them. Results from the review show that the BxPs and Standards are lacking to support the automation of clash resolution. Suggested potential changes to make these documents ready for the implementation of automation of clash resolution are discussed.

Key Words: BIM Execution Plan, BIM Standards, Automated Clash Resolution, Machine Learning, Amendments

Introduction

Mechanical, electrical, and plumbing (MEP) coordination is considered one of the most challenging coordination activities in construction project delivery with 57% of design coordination errors directly impacting the cost of construction (Mehrbod et al., 2019). This makes management of the design coordination process critical to achieving a cost-effective and quality project delivery (Mehrbod et al., 2019). Building Information Modeling (BIM) has a significant capability to improve the design coordination process with design coordination and conflict detection being the most used aspect of BIM (Mehrbod et al., 2019). The design coordination process is defined as the identification and solution of a problem across multiple disciplines to deliver a project design that meets the expected functional, aesthetical, and economical requirements of a project. An important task in design coordination is clash management, which includes clash detection and clash correction (Hu et al., 2020). BIM coordinators use BIM software to integrate models from multiple disciplines and detect clashes using the built-in functionalities of these software. Once found these clashes are discussed in design coordination meetings with trade specialists for potential solutions. Compared to the automation of clash detection the level of automation in the clash resolution and correction process is low (Hu et al., 2020). However, research is ongoing in automating clash resolution. Radke et al. (2009) created a plug-in for Revit MEP to automate clash resolution. The plugin-allowed to detect all clashes and automatically resolve them as per the user's input. Hu and Castro-Lacouture (2019) used supervised machine learning to automate the distinction between relevant and irrelevant clashes. Out of the 6 different supervise machine learning algorithms tested, the Jrip algorithm came out to be superior with an average accuracy reaching 80% in both training and testing of the datasets. utilized spatial relationships among building components to assist in the identification of irrelevant clashes and reduce the number of objects required to be moved to resolve clashes. Using query searches, Hu et al. (2019) were able to identify irrelevant clashes effectively along with clashes that were critical due to lack of enough room, and group of clashes that can be resolved by moving a single element. used a back-propagation neural network and heuristic optimization to automate clash resolution in the basement of a student residence. These experiments showed the effectiveness and feasibility of using automation systems for clash resolution.

The literature reveals that implementing Machine Learning to automate clash resolution and improve clash detection requires using information (attribute-based and geometric-based) embedded within BIMs making BIMs an integral part of the automation process. The success of information extraction using BIMs is highly dependent on the quality of data in the model . Thus, it is important to make certain that relevant and correct information is embedded into BIMs. One way to properly leverage embedded information is through standardization (Weygant, 2011). BIM execution plans (BxP) and standards are often used as tools to provide standardized workflow and general guidance to facilitate BIM implementation (breakwitharchitect, 2021). Therefore, the authors believe that as more research is being conducted toward automating clash resolution, a similar effort needs to be put forward to analyze current BxP and BIM standards so that future BIM development can support the implementation of the automation models. The goal of this paper is to extend the knowledge in developing BxP and BIM standards that support automated clash resolution. To support this knowledge goal the authors have three aims:

1. Conduct a comparative analysis of existing literature focused on the automation of clash resolution and identify information extracted from BIMs to support automated clash detection and resolution.
2. Conduct a comparative analysis of existing BIM standards and BxP and identify the gaps in the BIM standards and BxP.
3. Suggest amendments and addition to current BxP and BIM standards in support of automated model checking, specifically automated clash resolution.

Literature Review

There has been research into using BxP to support effective BIM implementation in support of facility operation and maintenance (O&M). Wu and Issa (2015) developed a BIM execution process model to support green BIM practices and improve LEED project outcomes. proposed and developed a BxP to support BIM model management for facility management during the O&M phase and tested its effectiveness using a building project case study. Rodrigues and Andrade (2021) proposed a BxP be implemented in the design sector of a Brazilian Public University. Their work highlighted the benefits and broad importance of the execution plan.

The authors reviewed three different industry standard Building Information Contract Guides that explain and supply guidance for how building information should be created, modified, and maintained to facilitate construction, planning, facility operations and maintenance, and space and asset management. The three guides are General Services Administration (GSA) Building Information Modeling (BIM) Guide 07 (GSA, 2007), ConsensusDocs 301 Building Information Modeling (BIM) Addendum (ConcensusDoc, 2016), and American Institute of Architect Digital Practice Documents (AIA, 2022).

GSA uses automated model checking in addition to manual checking to perform quality control at all design milestones and recommends its use by the design and construction team (GSA, 2016). The current GSA BIM Guide 07 Building Elements explains different types of building information and provides guidance on how such information can be created, modified, and maintained to support planning, construction, facility operation and maintenance, and space and asset management. The guide covers topics including levels of detail and level of development, model progression matrix, model element general requirements, naming conventions, guidance for modelers, model quality control using clash detection, and BxP.

As explained in ConsensusDocs 301 BIM Addendum Guidebook (2016) the ConsensusDocs 301 BIM Addendum is intended to be used on projects where early in the project, the project owner and major project participants commit to using BIM or virtual design and construction (VDC) and the design model is intended to be a contract document. The ConsensusDocs 301 BIM addendum incorporates what is believed to be the best practices in BIM use. The BIM addendum covers topics like the As-Built Construction Model which may include attribute-based information, level of detail specification, geometric modeling, BxP, data collection protocols, and model sharing and networking infrastructure.

The American Institute of Architects (AIA) Digital Document Guide (2022) explains the AIA 2022 Digital Practice Contract Document. These contract documents include BIM Exhibits E201, E202, E401, and E402, G203 BIM Execution Plan (BxP), and Model Element Table G204 and G205. These BIM exhibits focus on expectations related to the scope and authorized use of Digital Data and BIM. G203 serves as a framework for project participants in creating a project-specific BxP. G204 and G205 have detailed and abbreviated Model Element Tables respectively.

Methodology

To support the author's first objective, a comparative analysis of how BIM was utilized by researchers to develop their automated clash resolution models was conducted including information extracted from BIM that supports automated clash resolution. The comparative analysis is shown in Appendix A. The identified information was classified as either geometric or attribute information. Three BIM guides were then reviewed to identify topics related to 1) information required to be embedded into the BIMs, 2) project stages BIM can be utilized in, 3) BIM ownership and authorship, 4) BIM quality control, and 5) scope of BIM utilization. The selection of the three BIM guides was based on ease of availability and access to the documents. Additionally, selecting these three guides allowed an understanding of the point of view of different stakeholders when writing these guides. AIA (2022) provides insight on how designers want to utilize BIM. GSA BIM Guide (2016) is written from an owner's perspective, while the ConsensusDocs (2016) is written by a coalition of 40 national associations that includes Associated General Contractors of America, Association of Builders and Contractors, Construction Owners Association of America, American Subcontractors Association and

Mechanical Contractors Association of America. The authors are also aware that the US Army Corps of Engineers (USACE) and Military Construction (MILCON) also use BIM Standards and BxP. Due to security considerations for the military and the Department of Defense (DoD), these standards and guides are firewall-protected and access has not been granted at the time of paper preparation. As a result, these guides have not been reviewed.

From the literature review and the BIM guides, an analysis was done to assess and propose:

1. How the current BIM guides can support automated clash resolution,
2. How BIM guides can be improved upon by comparison among the guides reviewed,
3. Recommended changes and additions to BIM guides to enhance support of automated clash resolution.

Results

It was determined from the literature that Machine Learning was the focus point to automate and improve clash resolution and that both graphical and attribute information are being used to support the automation process (shown in Appendix A). Therefore, it can be assumed that at the stage where automated clash resolution will be implemented the BIM needs to be sufficiently developed in terms of embedded graphical properties and attributes. Without both graphical properties and attributes embedded in the model, automated clash resolution will be less successful. Appendix B compares the topics covered by the industry standard BIM guides reviewed.

The BIM implementation guides cover topics of BIM coordination with the GSA BIM Guide supplying the most comprehensive clash detection instruction focused on clash detection in both design and construction. GSA (2016) also provided three tiers of clash types based on how they can be resolved.

1. Tier 1 clash includes clashes that can be resolved by a single entity internally.
2. Tier 2 clash includes clashes that can be resolved by coordination between multiple consultants or subcontractors.
3. Tier 3 clash includes clashes that exist due to design issues and can only be resolved by design changes, budget changes, or both.

All three guides cover topics of BIM coordination, BIM quality control, and clash detection, yet lack meaningful direction on clash resolution. Absent from standards or guidelines are who is responsible for clash resolution, a dedicated project stage for clash coordination, who owns the resolved changes, building system resolution priority, and needed tools for clash resolution. Given the information required to be present in the BIM models to facilitate automation of clash resolution and the ownership of this information, the authors suggest that the guides recommend to owners that the Design-Build delivery method is the preferred method in support of automated clash resolution. Design-Build delivery will allow for early involvement of trade partners (sub-contractors) on the project, facilitating ease of information sharing and more time to make beneficial design decisions. Design-Build will also assist in mitigating the contract issues with authoring the model and owing the changes as both the project design and building firms are the same entity in Design-Build.

All three guides address Schematic Design Stage, Design Development Stage, Construction Document Stage, and Operation and Management stage but lack directions for a clash coordination stage. For example, the AIA Digital Document Guide (2022) in section 2.6 Model Coordination states, “If Project Participants discover or become aware of any discrepancies, inconsistency, errors, or omission in any Model Version, they shall promptly report the discrepancy, inconsistency, error, or omission in writing to the Author and the Architect.” This lack of a dedicated project stage for clash coordination has led to a missed opportunity to create standards for clash coordination in terms of what Level of Development (LOD) elements should exist by default during clash coordination and what information should be embedded into the model to support clash coordination and resolution. Furthermore, while reviewing the guides cases were noted where non-graphical (attribute) information was mentioned to be embedded into the BIM, but only to prepare the model for facility O&M. This was done to 1) support owners and facility managers' needs to use the handover/as-built BIMs for facility maintenance, and 2) to confirm that the BIM objects include necessary information like manufacturer, space type, model number, serial number, and O&M requirement.

The AIA guide (2016) acknowledges the industry trend toward Industry 4.0 and the development and utilization of Digital Twin. The guide notes how LOD 500 can support Digital Twin modeling (DTM) as DTM represents existing or as-built conditions using 3 primary frameworks.

1. LOD 500 model elements are field verified therefore they convey the as-built field conditions.
2. LOD 500 allows authors to embed non-graphical information into the model elements.
3. LOD 500 model elements must be accompanied by their level of accuracy. This can be reported using the U.S. Institute of Building Documentation (USIBD) Standard Level of Accuracy or a custom accuracy system.

Discussion

Although the guides demonstrate the potential for ease of implementation of an automation model for clash resolution there needs to be considerations made in terms of language changes and additional clauses to fully support the increased potential of fully automated clash resolution. Therefore, as part of the objective of this paper, the authors recommend amendments and changes to these guides in support of automated clash resolution. These changes are divided into two categories, one that directly supports implementing an automation model by providing the necessary information embedded into the model at the time of automation, and a second that indirectly supports the automation by suggesting administrative clauses that will address issues like automation change authorship. Recommendations to directly support the implementation of an automation-capable clash resolution model are:

1. Establish a dedicated phase for design/clash coordination: All three guides divide the project into multiple project phases along with providing tools like “Model Element Table” to make sure model elements are of an appropriate LOD and include agreed-upon non-graphical information. The inclusion of clash coordination as a project phase will allow project participants to contractually discuss and define all information to be included in the model during the clash coordination stage. This information can include both graphical information and attributes required by the automation model to predict clash resolution options.
2. Provide a detailed discussion on clash resolution and the automation option: Following the AIA lead in introducing Digital Twin, the author proposes a similar introduction be added to the guides regarding the automation of clash resolution. Similar to the Digital Twin introduction the guide can propose a preferred LOD for automated clash resolution and provide justification for how the chosen LOD can support the automation model.
3. Include non-graphical information as part of LOD: Currently, LOD focuses on the graphical representation of the model elements and categorizes the graphical development of the model elements. The authors suggest that the definition of LOD and its level be expanded to include non-graphical information as well. This will allow project participants to accurately choose

at what LOD level they can receive both appropriate graphical and non-graphical information for clash resolution support.

4. Expanding non-graphical information beyond O&M usage: Currently, the guides focus on using non-graphical information during the O&M project phase. As seen from the analysis of previous automation research non-graphical information in model elements is essential to support automating clash resolution. Therefore, the authors recommend that the scope of non-graphical information be expanded to include what information is essential at the clash coordination stage. This also ties back to the recommendation of considering a dedicated clash coordination phase in BxP and contracts.

While the above recommendations directly support a working automation model, consideration should also be made to support the implementation of the automation model at the administrative level. Therefore, proposed recommendations to indirectly support the implementation of automated clash resolution at the administrative level are:

1. The owner, designer, contractor, and trade contractors should agree on which elements they will perform clash tests on, and the need to model these particular elements at a specified LOD.
2. Currently, the guides do not comment on 1) how the machine learning clash resolved model will be named or transmitted, 2) who has the right to run the automated software and make changes to the model, and 3) what file format the resolved model will be transmitted. The owner, designer, prime, and trades contracts should determine the model author to finalize the automated changes. This can be the same party as the existing model authors or another party different from the one running the automated clash resolution. The project stakeholders also need to decide on whether the changes suggested by the automation model will be taken as suggestion that can be considered by the model authors or as mandatory changes that the authors have to make to the model.
3. Identification of the responsible party for running automated clash resolution and identification of model author to incorporate changes from automated clash resolution.
4. Language to propose the use of automation to support clash resolution can also be added to the guide such as, “To expedite the clash resolution process the Model Element Author(s) should use the specified automated clash resolution software. The Model Element Author(s) can use the clash resolution generated through the software as suggestions on how the clash can be potentially resolved.”
5. For the automation to work, all text-based values will have to be converted into a numerical value, selecting an appropriate Classification System to describe clashing element system types can help the automation to work better. While selecting the Classification System attention should be given to selecting a classification system that accurately describes the system type the model elements belong to as a numerical value.

Conclusion

Automating clash resolution that is correct and timely is on the horizon. The authors have attempted to initiate the thought process of looking at current industry BIM Guides/Standards and analyze if they are at par with the research being conducted in the construction industry to support construction workflow through automated processes such as the automation of clash resolution. Though research in the field of automation of clash resolution is still in its nascent stage, the literature shows significant advantages in the application of an automation model to support clash resolution and improve project delivery. Previous research relied heavily on the use of both graphical information and element attributes embedded into the BIMs. This makes the BIMs a critical component for the successful implementation of the automation model. Research has also shown that any successful implementation of BIM in a construction project is supported by a strong implementation of BxP and supporting document (breakwitharchitect, 2021; Lin et al., 2016; Rodrigues & Andrade, 2021; Weygant, 2011; Wu & Issa, 2015).

In this paper, the authors have reviewed three different BIM implementation guides, namely the AIA Digital Document Guide (2022), the General Service Administration BIM Guide 07 (2016), and the ConsensusDocs 301 BIM Addendum (2016). The goal was to understand how these documents presently support clash resolution and what changes would be required to support the future implementation of an automated clash resolution model. Based on the review of literature for automation of clash resolution and BIM guides, the authors have suggested several changes and additions both directly (changes focused on preparing BIMs for automation) and indirectly (administrative changes) to support the implementation of an automated clash resolution model. There are considerable opportunities to incorporate automated clash resolution guide requirements into industry BIM standards and BxP.

One of the limitations of this paper is that it does not consider the contractual liabilities and risks associated with the changes proposed. The main objective of this paper was to compare the BIM guides and BxPs to assess their readiness in supporting the implementation of the automated models for clash resolution. Based on this assessment, the authors propose how this documents can be amended to make them more automation ready to act as a starting point of discussion into amending our BIM guides and BxP. A study into the contractual liability and risk assessment of these proposed changes would require a deeper review of the literature and understanding of contractual liabilities associated with the use of BIM in construction projects. The authors look forward to inviting additional researchers in the area of construction contracts to further the research and contribution of knowledge in this area.

References

AIA (2022). AIA Digital Documents Guide. American Institite of Architects. https://www.aiacontracts.org/resources/6524822-2022-bim-documents-guide

breakwitharchitect. (2021). *Defining the BIM Execution Plan*. Retrieved 15 September from https://www.breakwithanarchitect.com/post/the-bim-execution-plan

Hsu, H.-C., Chang, S., Chen, C.-C., & Wu, I. C. (2020). Knowledge-based system for resolving design clashes in building information models. *Automation in Construction*, *110*, 103001. https://doi.org/https://doi.org/10.1016/j.autcon.2019.103001

Hu, Y., & Castro-Lacouture, D. (2019). Clash relevance prediction based on machine learning. *Journal of computing in civil engineering*, *33*(2), 04018060.

Hu, Y., Castro-Lacouture, D., & Eastman, C. M. (2019). Holistic Clash Resolution Improvement Using Spatial Networks. In *Computing in Civil Engineering 2019: Visualization, Information Modeling, and Simulation* (pp. 473-481). American Society of Civil Engineers Reston, VA.

Hu, Y., Castro-Lacouture, D., Eastman, C. M., & Navathe, S. B. (2020). Automatic clash correction sequence optimization using a clash dependency network. *Automation in Construction*, *115*, 103205.

Lin, Y.-C., Chen, Y.-P., Huang, W.-T., & Hong, C. (2016). Development of BIM Execution Plan for BIM Model Management during the Pre-Operation Phase: A Case Study. *Journal of Buildings*, *6*(1), 1-14.

Mehrbod, S., Staub-French, S., Mahyar, N., & Tory, M. (2019). Beyond the clash: investigating BIM-based building design coordination issue representation and resolution. *J. Inf. Technol. Constr.*, *24*, 33-57.

Radke, A., Wallmark, T., & Tseng, M. (2009). An automated approach for identification and resolution of spatial clashes in building design. 2009 IEEE International Conference on Industrial Engineering and Engineering Management,

Rodrigues, I., & Andrade, M. (2021). BIM Execution Plan (BEP) to Infrastructure Superintendence of the Federal University of Pernambuco: A Proposal to Implement BEP in a Federal University in Brazil.

Weygant, R. S. (2011). *BIM content development: standards, strategies, and best practices*. John Wiley & Sons.

Wu, W., & Issa, R. R. (2015). BIM execution planning in green building projects: LEED as a use case. *Journal of Management in Engineering*, *31*(1), A4014007.

Appendix A

Appendix A

BIM information used to support automation of BIM clash resolution

Mark	Category	BIM Information	Radke, et. al., (2009)	Hu and Castro-Lacouture (2019)	Huang and Liu (2019)	Hsu et al. (2020)
1		**Start Point:** Clashing elements' X/Y start point.	X			X
2		**End Point:** Clashing elements' X/Y end point.	X			X
3		**Base Level:** Z coordinate of clashing element.	X			
4		**Thickness:** Clashing element's thickness.	X			
5		**Radius:** Circular clashing element's radius.	X			
6		**Height:** Square clashing element's height.	X			
7		**Width:** Square clashing element's width.	X			
8		**Shape:** Clashing element's shape.		X		
9	GI	**Clashing Volume:** Volume of clash.		X		
10		**Spatial relationship:** If the clash exists beyond the ceiling or not.		X		
11		**Available space:** Available space around clash.		X		
12		**Clearance:** Clashing elements' clearance requirement.	X			
13		**Cross-sectional area:** Clashing element's area.		X		
14		**Clash Type:** Parallel or cross-type clash.				X
15		**Intersection Type:** Penetrating or punching clash.				X
16		**Distance:** Clashing elements' overlap distance.			X	
17		**Clash Point:** 3D coordinates of the clash.			X	
18		**Material:** Material of clashing element.		X		
19		**System Type:** Clashing elements'building system.	X	X		X
20	AI	**Class:** Class of clashing element. Eg. pipes, ducts.		X	X	
21		**Information Uncertainty:** Uncertainty regarding the clashing element.		X		
22		**Location:** Location of the clash. Eg. floor, room.		X	X	

23	**Priority:** Clashing elements' movement priority.	X	

GI = Geometric Information AI = Attribute Information

Appendix B

Appendix B

Topics covered in different BIM Guides

Mark	Topic	AIA Digital Document Guide	ConsensusDocs 301	GSA BIM Guide 07
1	BIM as Contract Document	X	X	
2	Level of Development	X	X	X
3	BIM Execution Plan	X	X	X
4	Non-Graphic Information in BIM	X	X	
5	BIM Sharing	X	X	
6	BIM Reliance	X	X	
7	BIM Coordination	X	X	X
8	Operation and Management Project Stage	X	X	X
9	Digital Twin	X		
10	BIM Authorship	X	X	
11	Modeling Software	X	X	X
12	Data Security	X	X	
13	File Naming Conventions	X	X	X
14	Project Participants Responsibility	X	X	X
15	BIM Quality Control	X	X	X
16	Conceptual Planning Project Stage		X	
17	Schematic Design Project Stage	X		X
18	Design Development Project Stage	X	X	X
18	Construction Document Project Stage	X	X	X
20	As-Built Model	X	X	X
21	Civil Information Modeling		X	
22	Coordinated Construction Model		X	X
23	Design Model		X	X
24	4D Scheduling		X	X*
25	5D Scheduling		X	
26	Model Ownership		X	
27	IFC Models			X
28	COBie		X	X
29	Project Delivery Method			X

X* topic covered in GSA BIM Guide 04

Statement to Address Reviewers' Comments

Dear respected reviewers,

Please find attached my revised manuscript titled Impact of Supplementary Cementitious Materials on Alkali-Silica Reactivity of Concrete.

Since I received no technical comments, I have reviewed the paper format, spelling, and grammar. I am attaching the final manuscript for possible publication in your esteemed conference.

Impact of Supplementary Cementitious Materials on Alkali-Silica Reactivity of Concrete

Alkali-silica reactivity (ASR) is a deleterious reaction initiated in hardened concrete when aggregates silica reacts with alkali hydroxide in portland cement in the presence of high moisture. The ASR results in the formation of expansive gel which induce internal stresses in hardened concrete, and may lead to concrete cracking, spalling, and possibly structure failure. The main objective of this research is to investigate the impact of supplementary cementitious materials (SCMs) on the gel-formation, and the possible use of SCMs in mitigating ASR damage on hardened concrete. In this research, different types of aggregates were used to pour ASR test specimens, and ASR mortar bar tests were conducted according to relevant ASTM standard specifications. Additional concrete specimens were poured using different percentages of SCMs, mainly silica fume, class c fly ash, and ASR testing was repeated to assess the SCMs impact on ASR. The research outcomes showed that fine SCM particles used in concrete mixes can halt the concrete expansion due to ASR. SCMs efficiency in mitigating ASR is directly proportional to the SCM particle size. The successful use of SCMs in mixing concrete will reduce the rate of hardened concrete deterioration, limit the need to maintenance and repair, and reduce the life cycle cost of concrete construction projects.

Key Words: Alkali-Silica Reactivity, ASR, Silica Fume, Fly Ash, Aggregates, Mortar Bar Test

Introduction

Alkali-silica reactivity (ASR) was first identified as a possible cause for hardened concrete deterioration in California in the 1940s. ASR is a deleterious chemical reaction which start when active silica found in specific types of aggregates reacts with the alkaline hydroxide of portland cement. The deleterious ASR is catalyzed by the presence of moisture content within hardened concrete. As a result of ASR, expansive, white-colored gel-like substance is formed within concrete, which adds internal tensile stress to the hardened concrete as it ages. The white gel-formation could be detected using petrographic analysis of hardened concrete specimens obtained by core drilling (ASTM C 295), as shown in Figure 1.

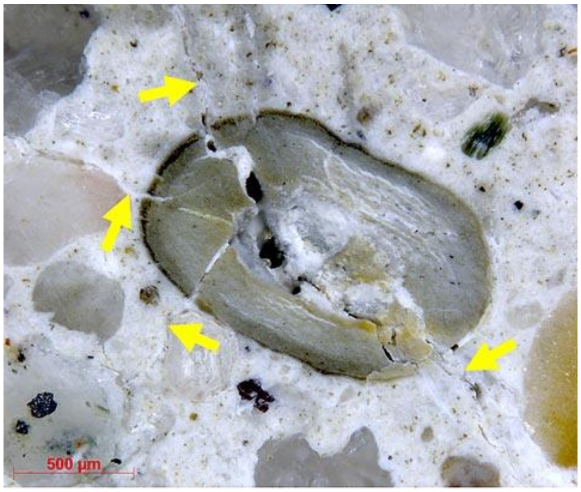

Figure 1. ASR expansive gel as shown in petrographic analysis of hardened concrete (courtesy of FHWA labs)

The ASR mechanism can be explained as a two-step chemical reaction, as per the following equations:

Alkali hydroxides (in portland cement) + Reactive silica (in aggregates) $\longrightarrow$ ASR gel [1]

ASR gel + Moisture (within hardened concrete) $\longrightarrow$ Gel expansion (internal stresses) [2]

The internal stresses generated due to the expansion of formed gel induces escalating internal stresses as the concrete ages. The rate of stress increase is proportional to the amount of reactive silica present in the concrete aggregates content, the moisture content within hardened concrete, and the surface area of the concrete structure exposed to air. ASR is known to result in significant deterioration of concrete infrastructure projects, as shown in Figure 2, due to their large-exposed surfaces, and the possible ingress of moisture.

Figure 2. ASR damage in highway barrier (Deschenes Jr., 2017)

Literature Review

ASR destructive effect to hardened concrete and the premature failure of concrete sections were first explained in the Unites States in the 1940s (Stanton, 1940). Based on Stanton discovery, multiple concrete structures failures were investigated, and ASR was found responsible for the premature distress including hydraulic plant premature failure in Virginia (Kammer and Carlson, 1941). In order for ASR mechanism to work, coarse and/or fine aggregate used should contain reactive silica to react with portland cement alkaline content. Sufficient moisture resulting from mixing water (that didn't react with cement during hydration) or external moisture ingress to hardened concrete through concrete voids is required to catalyze the reaction as the concrete ages. ASR components are shown in Figure 3.

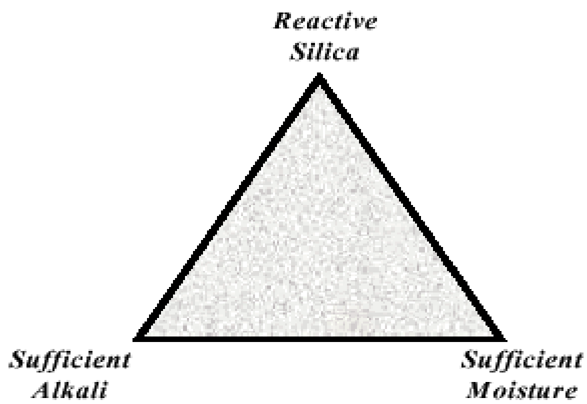

Figure 3. Components required to initiate destructive ASR (Thomas et al., 2007)

Recent studies provided detailed explanation for ASR (Akhnoukh and Mallu, 2022, Wang et al., 2022, Fanijo et al., 2021, Abd-Elssamd et al., 2021 and 2020, and Akhnoukh et al., 2016). During concrete mixing, the aggregate content (gravel, limestone, sand, or crushed granite) is encapsulated with hydrated portland cement with high alkaline content (pH value of hydrated cement may reach 13.5). When cement hydration is concluded and the concrete hardens, the remaining (unused) mixing water and moisture dissipating through hardened concrete voids forms a strong alkaline solution which is capable of dissolving particular silicious content within the aggregate to form the white gel particles. As the hardened concrete ages, the formed gel reacts with moisture to expand, and internal stresses are applied to hardened concrete. The magnitude of ASR damage to concrete depends on (1) the type and quantity of reactive silicious content; (2) the amount of free moisture resulted from the unused mixing water; and (3) the ingress of moisture through the hardened concrete capillary voids (concrete voids ratio and permeability).

Several research projects investigated different alternatives to reduce ASR and/or mitigate its destructive impact on hardened concrete. Proposed ASR mitigation techniques include (1) the use of chemical admixtures (lithium salts) to halt ASR (Carles-Gibergues et al., 2007); (2) the use mineral admixtures, also known as supplementary cementitious materials (SCMs) as silica fume, quartz flour, fly ash, blast furnace slags, metakaolin, and multi-wall carbon nanotubes (MWCNTs) (Chihaoui et al., 2022, Luo et al., 2022, Akhnoukh and Buckhalter 2021, Akhnoukh, 2020, 2018, and 2016, Figueira et al., 2019, Kawabata and Yamada, 2017, and Elia et al. 2017); and (3) the use of chemical and latex surface painting to prevent the moisture dissipation in hardened concrete (Deschenes et al., 2017). The main objective of this research is to investigate the possibility of ASR mitigation using class C fly ash, silica fume. In order to attain the research objective, accelerated mortar bar testing for concrete specimen is conducted, and specimen expansion is measured. Measured expansion is evaluated according to ASTM C1293-20 standard specifications, and is used to assess the reactivity of aggregates and the effectiveness of SCMs in mitigating ASR impact on hardened concrete.

Experimental Investigations

The accelerated mortar bar test (AMBT) developed in South Africa in the 1980s is used to identify possible reactivity of different aggregates. The AMBT adopted by multiple specifications as ASTM International, AASHTO, Canadian Standard Specification, and Portland Cement Association (PCA) is conducted using a standard prism mold of 1x1x11.25 in. (2.5 x 2.5 x 28.1 cm.) to fabricate mortar bars using the aggregate to be tested. The AMBT spans for 16 days before the potential reactivity or the impact of SCMs on ASR is reported. Length changes of fabricated bars are measured and reported during the test duration (ASTM C 1293). A total expansion less than 0.1% of the original bar length is acceptable as the used aggregate is considered non-reactive. In addition, the reduction in expansion when different SCMs are used is an indicator of SCMs efficiency in mitigating ASR in hardened concrete members.

In this research, fine aggregates were obtained from 3 different queries to investigate aggregate reactivity, and the efficiency of silica fume and class C fly ash in mitigating ASR. Fifteen AMBT specimens were fabricated using the aggregates obtained from the three different sources, denoted as aggregates A, B, and C. Five different specimen mix designs were fabricated using each aggregate source (a total of 15 different material designs). Mix designs were selected based on aggregate source and SCMs content, as shown in Table 1.

Table 1.

Accelerated mortar bar specimen constituent combination (based on aggregate source and SCM content)

Sample	**Aggregate**	**Silica Fume**	**Class C Fly Ash**
Control – A	Fine aggregate (A)	0% SCMs	
A15SF		15%	0%
A30SF		30%	0%
A15FA		0%	15%
A30FA		0%	30%
Control – B	Fine aggregate (B)	0% SCMs	
B15SF		15%	0%
B30SF		30%	0%
B15FA		0%	15%
B30FA		0%	30%
Control – C	Fine aggregate (C)	0% SCMs	
C15SF		15%	0%
C30SF		30%	0%
C15FA		0%	15%
C30SF		0%	30%

Three mortar bars were fabricated for each AMBT specimen mix designs. The average expansion for the three bars is recorded at day 1 (original length), and at days 4, 7, 10, 13, and 16 to calculate bars expansion. During the 16-day duration of the AMBT test, specimens were stored in a sodium hydroxide solution at a temperature of 176 $\pm$ 3.6 F. Specimens are stored in this harsh environment to expedite potential ASR in a short period of time as sodium hydroxide solution serves as a catalyst to ASR. Accelerated Mortar bar specimens and measurement of specimens' expansion are shown in Figure 4.

(a) (b)

Figure 4. (a) AMBT specimens, and (b) Expansion testing for fabricated specimens

The average expansion of control specimens for aggregates A, B, and C is measured to evaluate the potential aggregate reactivity. Measured expansion for control specimens (A, B. and C) as a percent of the original length of the mortar bars at 16-day age were 0.082%, 0.07%, 0.06%. Detailed result for mortar bar expansions during different testing days is shown in Figure 5. According to ASTM C1293, silica content in the three aggregate sources is considered non-reactive (final expansion < 0.1%).

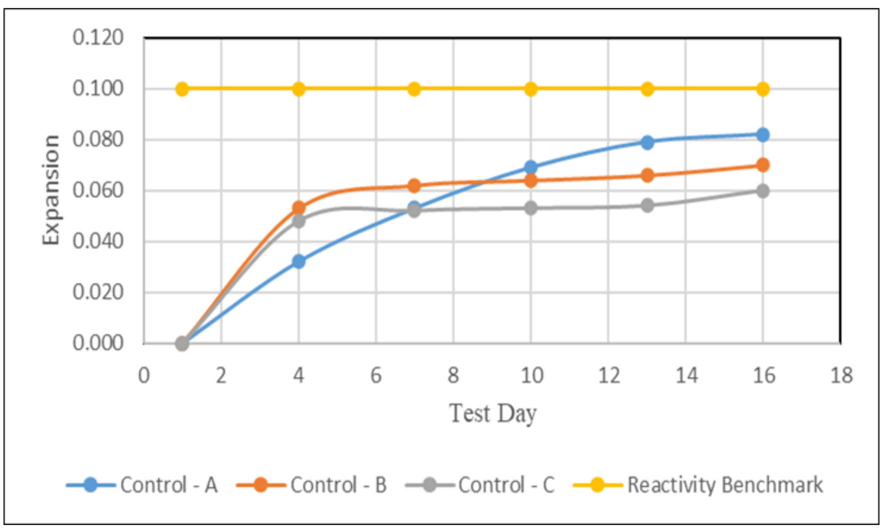

Figure 5. Expansion of control specimens (16-day results)

In order to investigate the efficiency of SCMs in mitigating ASR, the decrease in bars expansion after 16 days of measurement for specimens fabricated using class C fly ash and silica fume is calculated as a percent of the control specimen expansion. Test results showed that SCMs successfully reduce concrete expansion due to ASR. Silica fume displayed higher ability to reduce the final expansion. The effect of SCMs is directly proportional to their percentage in the concrete mix. Detailed results are shown in Figure 6.

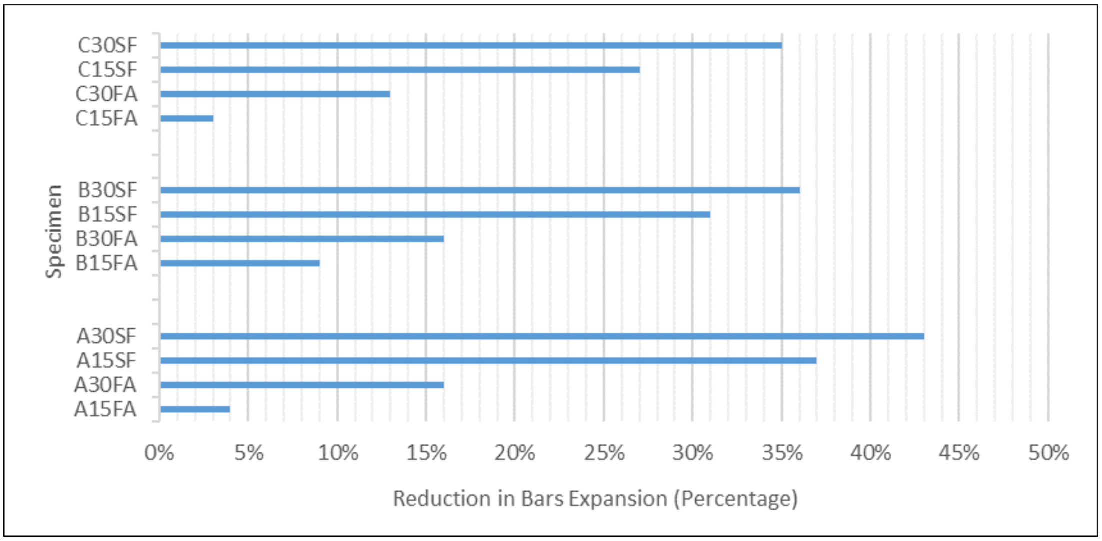

Figure 6. Reduction in mortar bars expansion vs. SCMs type and percentage

Conclusions

ASR is a deleterious effect that results in concrete project deterioration. ASR could be detected through different testing techniques including petrographic analysis of concrete cores, and accelerated mortar bar testing (AMBT) for laboratory-fabricated specimens. In this research, aggregates obtained from three different sources were evaluated for ASR using AMBT. Control specimens fabricated using the three aggregates, and no SCMs, were tested for 16-day expansion. Test results showed that the three sources resulted in mortar bars expansion less than 0.1%, which indicates that aggregates tested are non-reactive. AMBT was conducted for different specimens fabricated using different percentages of class c fly ash and silica fume to assess their potential impact on hardened concrete expansion. The following conclusions are made based on SCM incorporated specimens' tests outcomes:

- SCM incorporation in concrete mixes results in reducing the hardened concrete expansion as calculated by AMBT. This indicates that SCMs can be used in concrete mix designs to mitigate ASR of aggregates with high reactivity
- Silica fume is more efficient in mitigating ASR. This could be attributed to the smaller particle size of silica fume, which reduces concrete porosity; thus slow the ingress of moisture required to catalyze the ASR
- SCMs ability to reduce ASR is proportional with their percentage of incorporation in the concrete mix. The decrease in bars expansion is more sensitive to the increase in fly ash content as compared to silica fume

- Portland cement replacement by 15% silica fume or 30% fly ash (by weight) results in a significant decrease in ASR. The percentage of expansion decrease due to SCMs incorporation is associated with comparable compressive strength increase as a result of SCMs incorporation in concrete mix design (Akhnoukh and Elia 2020, Akhnoukh 2019 and 2008, Zackary et al., 2018, and Graybeal and Hartman, 2008)

The successful mitigation of ASR in concrete construction projects in general, and transportation infrastructure in particular, will significantly improve projects conditions, increase their service life, and reduce the need to maintenance and/or repair activities during the life span of the project.

Recommendations for Future Research

The petrographic analysis of hardened concrete and the lab experimental investigation is labor intensive and may result in injuries for researchers, lab personnel, and labors while conducting their ASR testing. Specific safety measures for ASR testing should be developed and enforced to ensure safety of conducted site and lab work.

References

Abd-Elssamd, A., Ma, Z.J., Hou, H., and Le Pape, Y., "Influence of mineralogical and chemical composition of AAR carbonate aggregates on the expansion rate of concrete and AAR mitigation," Construction and Building Materials, Vol. 261, 2021, https://doi.org/10.1016/j.conbuildmat.2020.119916

Abd-Elssamd, A., Ma, Z.J., Le Pape, Y., Hayes, N.W., and Guimaraes, M., "Effect of alkali-silica reaction expansion rate and confinement on concrete degradation," ACI Materials Journal, Vol. 117, No.1, 2020, 265-277 doi:10.14359/51720294

Akhnoukh, A.K., "The use of micro and nano-sized particles in increasing concrete durability," Particulate Science and Technology Journal, Vol. 38, No. 5, 2020, pp. 529-534 https://doi.org/10.1080/02726351.2018.1467988

Akhnoukh, A.K., "Accelerated bridge construction projects using high performance concrete," Elsevier Journal of Case Studies in Construction Materials, Vol. 12, 2020, https://doi.org/10.1016/j.cscm.2019.e00290

Akhnoukh, A.K., and Elia, H., "Developing high performance concrete for precast/prestressed concrete industry," Elsevier Journal of Case Studies in Construction Materials, Vol. 11, 2019, https://doi.org/10.1016/j.cscm.2019.e00290

Akhnoukh, A.K., "Development of high performance precast/prestressed bridge girders," A Dissertation, University of Nebraska-Lincoln, Nebraska, USA, 2008

Akhnoukh, A.K., "Implementation of nanotechnology in improving the environmental compliance of construction projects in the United States," Particulate Science and Technology Journal, Vol. 36, No. 3, 2018, pp. 357-361, https://doi.org/10.1080/02726351.2016.1256359

Akhnoukh, A.K., and Buckhalter, C., “Ultra-high-performance concrete: constituents, mechanical properties, applications, and current challenges,” Elsevier Journal of Case Studies in Construction Materials, Vol. 15, 2021 https://doi.org/10.1016/j.cscm.2021.e00559

Akhnoukh, A.K., Kamel, L.Z., and Barsoum, M.M., “Alkali silica reaction mitigation and prevention measures for Arkansas local aggregates,” International Journal of Civil and Environmental Engineering, Vol. 10, No. 2, 2016, pp. 95-99 doi.org/10.5281/zenodo.1338860

Akhnoukh, A.K., and Mallou, A.R., “Detection of alkali-silica reactivity using field exposure site investigation,” Proceedings of the 58th Annual Associated Schools of Construction International Conference, Georgia, 2022

ASTM C 1293C-14, “Standard test method for determination of length change of concrete due to alkali-silica reaction,” ASTM International, 2020 DOI: 10.1520/C1293-20A

ASTM C 295-08, “Standard guide for petrographic examination of aggregates for concrete,” ASTM International, 2011 DOI: 10.1520/C0295-08

Chihaoui, R., Siad, H., Senhadji, Y., Mouli, M., Nefoussin, A.M., and Lachemi, M., “Efficiency of natural pozzolan and natural perlite in controlling the alkali-silica reaction of cementitious materials,” Elsevier Journal of Case Studies in Construction Materials, Vol. 17, 2022, https://doi.org/10.1016/j.cscm.2022.e01246

Deschenes Jr., R.A., “Mitigation and evaluation of alkali-silica reaction (ASR) and freezing and thawing in concrete transportation structures,” A Dissertation, University of Arkansas at Fayetteville, 2017

Fanijo, E.O., Kolawole, J.T., and Almakrab, A., “Alkali-silica reaction (ASR) in concrete structures: mechanism, effects and evaluation test methods adopted in the United States,” Elsevier Journal of Case Studies in Construction Materials, Vol. 15, 2021, https://doi.org/10.1016/j.cscm.2021.e00563

Figueira, R.B., Sousa, R., Coelho, L., Azenha, M., De Almeida, J.M., Jorge, P.A.S., and Silva, C.J.R., “Alkali-silica reaction in concrete: mechanism, mitigation and test methods,” Elsevier Journal of Construction and Building Materials, Vol. 222, 2019, pp. 903-931, https://doi.org/10.1016/j.conbuildmat.2019.07.230

Graybeal, B.A., and Hartmann, J.L., “Strength and durability of ultra-high-performance concrete,” Proceedings of the Concrete Bridge Conference, 2003

Haber, Z.B., De La Varga, I., Graybeal, B.A., Nakashoji, B., and El-Helou, R., “Properties and behavior of UHPC-class materials,” Federal Highway Administration Publication No. FHWA-HRT-18-036, 2018

Kawabata, Y., and Yamada, K., “The mechanism of limited inhibition by fly ash on expansion due to alkali-silica reaction at the pessimum proportion,” Cement and Concrete Research, Vol. 92, 2017, pp. 1-15 https://doi.org/10.1016/j.cemconres.2016.11.002

Lou, D., Sinha, A., Adhikari, M., and Wei, J., “Mitigating alkali-silica reaction through metakaolin-based internal conditioning: new insights into property evolution and mitigation mechanism,” Cement and Concrete Research, Vol. 159, 2022, https://doi.org/10.1016/j.cemconres.2022.106888

Thomas, M.D.A., Fournier, B., Folliard, K.J., Ideker, J.H., Resendez, Y., “The use of lithium to mitigate alkali-silica reactivity (ASR),” Federal Highway Administration Publication Number FHWA-HRT-06-133, 2007

Kammer, H.A., and Carlson, R.W., “Investigation of causes of delayed expansions of concrete in buck hydroelectric plant,” American Concrete Institute Journal, Vol. 3, No. 7, 1941, pp. 665-671

Stanton, T.E., “Expansion of concrete through reaction between cement and aggregates,” Proceedings of the American Society of Civil Engineers, Vol. 66, New York, 1940, pp. 1781-1811

Wang, W., Noguchi, T., and Maruyama, I., “Mechanism understanding of alkali-silica reaction in alkali-activated materials system,” Cement and Concrete Research, Vol. 156, 2022, https://doi.org/10.1016/j.cemconres.2022.106768

Implementation of a Time Management Training Module for Freshmen Students in an Entry Level Construction Management Course

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Chico, CA

The transition to a four-year university presents many new challenges for freshmen students transitioning from high school. Students are thrust into a situation where they are solely responsible for balancing a variety of responsibilities, ranging from completing assigned coursework, studying for exams, along with personal and social obligations. Not surprisingly, this freshmen year is the most critical timeframe in determining whether a student will persist at a four-year university. Approximately 1 in 5 freshmen will either change schools or dropout out of their university during the first year. Construction students face additional challenges given their personality tendencies. Effective time management behaviors have demonstrated improved academic performance and increased the likelihood students will persist until graduation. Unfortunately, time management practices are rarely taught at universities and students are expected to learn these behaviors on their own. This paper will demonstrate the implementation of a time management module in a first-year construction management course and assess whether this training resulted in improved academic performance for freshmen construction students.

Key Words: Time Management, Student Training, Student Preparedness, Student Persistence, Academic Performance

Background

The first year attending a four-year college is a challenging transition for many students. Often this is the first time these young adults have moved out on their own and no longer have the stability and guidance of their parent(s) or guardian(s) in an established home environment. As a result, first-year students are thrust into a situation where they must act more independently and display more initiative in comparison to their high school lifestyle (Maloshonok, 2017). It should come as no surprise that students experience higher levels of stress and feelings of uncertainty during the first couple of months upon arriving at a higher education institution (Maloshonok, 2017).

A survey of incoming freshmen found that 60% of students “lacked the necessary learning and studying strategies of attitude, time management and study aids” to successfully transition from high school to a university (Mills, 2012). This lack of preparedness is reflected in the persistence rates of incoming freshmen. According to the National Center for Education Statistics, approximately 82% of freshmen persisted or remained at the same public university over a 3-year period between 2011 and 2014. Conversely, 18% of freshmen students either dropped-out completely from school or changed universities (McFarland et al., 2017).

Given these shortcomings in persistence, it is worthwhile to consider how freshmen students can be better prepared to handle the additional responsibilities of college. Specifically, construction students demonstrate certain tendencies, which can lead to additional challenges throughout their freshmen year (Mills, 2012). Time management is a critical skill that when developed, will greatly benefit first year students in meeting the demands of higher education. It has been demonstrated that proficient time management behavior leads to reduced stress and anxiety, as well correlates to higher performance amongst higher education students (Adams, 2019). Fortunately, time management behaviors can be improved through knowledge, training, or deliberate practice (MacCann et al., 2012).

CMGT 100 – Concepts of Construction is the first course for Construction Management (CMGT) students at California State University, Chico. This class is made up of freshmen, sophomore and junior level construction management students. As the instructor of this course, the author has observed first-hand the struggles for freshmen students in this class. In an effort to improve student performance, the author implemented a series of time management modules as assignments in this course throughout the Spring 2022 semester. This paper will discuss the implementation of the time management training modules, analyze the results, and review the findings to determine if the time management curriculum resulted in improved academic performance for freshmen construction management students.

Literature Review

Time management can be viewed as “behaviors that aim at achieving an effective use of time while performing certain goal-directed activities” (Hafner et al., 2013). To effectively do so, a basic time management practice consists of identifying tasks, ranking these tasks in terms of importance or priority, and then elect the time and resources to complete each task (Macan et al., 1990). Fortunately, time management is a set of behaviors or habits that can be trained and improved amongst students. (MacCan et al., 2012). Studies have demonstrated after time management training, participants were likely to frequently implement time management practices, resulting in better prioritization of tasks, more accurate estimates of durations to complete tasks and reduced procrastination (Kader, 2015).

The first year of study at higher education institutions is often the most critical time period when it comes to determining whether a student will return for a second year and ultimately receive their degree (Meer et al., 2010). According to the Education Data Initiative, 18.4% of full-time, first-time college freshmen dropped out between 2019 – 2020 (Hanson, 2022). Furthermore, most students who leave higher education elect to do so during or immediately after the first year (Meer et al., 2010). A big reason for the struggles of these students is the sudden demand to manage their time outside of the classroom. The majority of learning in high school takes place in-class, while up to 500% more outside of class study time is required in college (Bradley, 2006). This puts more responsibility and pressure on students to effectively manage their time and is often a harsh reality-check. In a study and survey of 1,020 engineering freshmen at North Carolina State University (NCSU), after the first semester, 25% or approximately 255 of the students indicated poor time management as their main concern and something they would change if they could start the semester over again (Bernold, 2007). Poor time management behaviors such as not allocating enough time for assignments, cramming for exams, and missing assignment deadlines, often result in increased stress and poor academic performance (MacCann et al., 2012). Time management is especially important for construction students due to their general personality tendencies. According to Mills, “students majoring in construction are typically more assertive, risk taking, action-oriented individuals who learn more by doing than by thinking” (Mills, 2012). Furthermore, construction students are typically self-reliant, optimistic of success against extreme odds, and delay in requesting help. As a result, these students can become disengaged with learning, resulting in lower grade point averages, lower rates of retention, and students transferring out of the curriculum (Mills, 2012).

Currently, the majority of higher education institutions do not provide much in terms of support to assist students in navigating the additional work-life responsibilities as they transition from high school (Adams, 2019). Experts argue that teaching and administrative staff at higher education institutions should actively guide and train students to understand time management behaviors and skills (Meers et al., 2010). When a time management program is effectively implemented in the classroom, the students reap the benefits. For example, Baylor University implemented a 12-week time management training in a freshmen level engineering course, which produced positive results such as improved GPA and increased retention within the engineering major (Bradley, 2006). Bernold reports that students who displayed effective time management habits were more motivated and in general had higher GPA’s then their peers who lacked these habits (Bernold, 2007).

Time management is a critical skill for construction students not only to manage their schoolwork, but also benefits their future careers as construction managers. A survey of construction alumni listed “time management” as a critical skill for construction management students to be proficient in upon entering the workforce. Lee et al., argue construction programs would benefit from teaching these time management skills within construction classes (Lee et al., 2011). A study analyzing time management training for entry level construction students has not yet been conducted. This research paper aims to address this particular topic with the intent the discussed practices can be utilized and implemented by construction faculty at other construction programs, to the benefit of the larger population of first-year construction students.

Methodology

The CMGT 100 class consisted of 31-students, 9 of which were freshmen and the other 22 of which were sophomores or juniors. At the beginning of the semester the author issued a pre-survey to assess the current time management behaviors of the students in the CMGT 100 class. A 5-point Likert scale was utilized to solicit student responses, which consisted of: 5-strongly agree (SA), 4-agree (A), 3-neutral (N), 2-disagree (D), and 1-strongly disagree (SD) for the following questions:

1. Question #1: I have a system in place to plan and manage my weekly tasks
2. Question #2: Before the start of a new week, I spend time reviewing all the upcoming assignments for the week
3. Question #3: During the school week, I take at least 5-minutes a day to plan my priorities for the upcoming day

After the pre-survey, the instructor created a template document in a spreadsheet software as the basis for the upcoming weekly time management (TM) assignments. These TM assignments were incorporated into the existing course curriculum as weighted assignments and were graded based on completeness. The TM template accounted for the basic elements of an effective time management practice: identifying tasks, ranking these tasks in terms of importance or priority, and electing the time and resources to complete each task (Macan et al., 1990). For each of their university classes, students were to list any assignments or tasks they were required to complete for the upcoming week and add these assignments to the TM template, see Figure 1. An assignment or task was defined as any course assigned task which had points associated with it, such as homework assignments, reports or research papers, reading assignments, quizzes, or exams. The instructor provided an additional instruction document, which explained the TM requirements and how to correctly complete the TM template. The students completed the TM template each week, for a duration of 10-weeks.

Assignment Log: Week of (Input Monday Date Here)						
Class	Tasks/Scheduled Activities	Due Date	Priority	Anticipated Hours to Complete This Week	Actual Hours to Complete	Delta Between Anticipated & Actual
Insert Class Number						
	Input Assignment Number & Name	Due Date	Priority #	Anticipated # of Hours	Actual # of Hours Spent	Input Delta
	Input Assignment Number & Name	Due Date	Priority #	Anticipated # of Hours	Actual # of Hours Spent	Input Delta
Insert Class Number						
	Input Assignment Number & Name	Due Date	Priority #	Anticipated # of Hours	Actual # of Hours Spent	Input Delta
	Input Assignment Number & Name	Due Date	Priority #	Anticipated # of Hours	Actual # of Hours Spent	Input Delta

Figure 1: Sample of weekly TM template provided to students

In addition to completing the TM template, the students were also required to complete a weekly re-cap survey. This survey had the students reflect on their TM behaviors from the previous week by asking the following questions:

1. Question #1: Reflecting on how you managed your time last week, what is an area of improvement that you will focus on implementing for this upcoming week?
2. Question #2: How many assignments (For all your classes) did you miss or fail to turn-in by the deadline?

At the end of the semester, the students were issued a post-survey to assess the students' experiences and perception of the time management modules. This survey utilized the following 5-point Likert scale for 3 of the questions: 5-strongly agree (SA), 4-agree (A), 3-neutral (N), 2-disagree (D), and 1-strongly disagree (SD). The survey also asked 2 open-ended questions for student input. The following shows the complete list of the post-survey questions issued to the students:

1. I plan to implement a system similar to the TM activities (Likert)
2. The TM activities improved my academic performance (Likert)
3. I would have missed more assignment deadlines without the TM activities (Likert)
4. What worked well and was beneficial from the TM activities? (Open-Ended)
5. What didn't work well for you or was a problem with the weekly TM activities (Open-Ended)

For each pre-survey, weekly re-cap survey and post-survey, students were required to input their academic status as either a freshmen, sophomore or junior standing. Freshmen students are the focus of this study so it was important the data could be separated to isolate those responses that came from freshmen students versus those responses from the more experienced sophomore and junior students.

Data and Findings

Pre-Survey Data and Findings

The data from the pre-survey was summarized and analyzed to identify the students' baseline time management behaviors. This pre-survey achieved a response rate of 90% (28 of the 31 students responded). The data was separated to breakout the responses from freshmen students versus that of the sophomore and junior standing students. This was done to establish a baseline of incoming behaviors and verify if indeed the freshmen students were less effective in their time management habits when compared to the sophomore and junior students. The following shows the main findings from this survey data:

1. Question #1: I have a system in place to plan and manage my weekly tasks.
    - Freshmen: 44% either strongly disagreed or disagreed with this statement, 34% were neutral and 22% agreed (mean value = 2.4).
    - Sophomores and Juniors: 19% either strongly disagreed or disagreed with this statement, 41% were neutral and 40% either agreed or strongly agreed (mean value = 3.3).
2. Question #2: Before the start of a new week, I spend time reviewing all the upcoming assignments for the week.
    - Freshmen: 25% agreed with this statement, 62% were neutral and 13% disagreed (mean value = 3.1).
    - Sophomores and Juniors: 65% either agreed or strongly agreed with this statement and the remaining 35% were neutral (mean value = 3.9).
3. Question #3: During the school week I take at least 5-minutes a day to plan my priorities for the upcoming day:
    - Freshmen: 50% either agreed or strongly agreed, 37% were neutral and 13% disagreed (mean value = 3.5).
    - Sophomores and Juniors: 65% either agreed or strongly agreed with this statement and the remaining 15% were neutral and 20% disagreed (mean value = 3.8).

The data from Question # 1 aligns with much of the literature research; freshmen students in particular often do not have well established time management behaviors. The sophomore and junior students have navigated the critical first 12 months at the university and have acquired more effective time management habits. Planning ahead is a critical aspect of time management and the results from Question #2 align with previous research; a high proportion of these freshmen students are not looking ahead and planning their tasks. Contrast this with the sophomore and junior students who demonstrate a much higher prevalence in planning and looking to the week ahead. Question #3 data shows these freshmen students tend to focus on short-term or more imminent tasks, rather than long range planning. The sophomore and junior level students show a consistent rate of looking ahead throughout the week, as well as taking time to plan the short-term or next day's tasks as well. This survey data indicates the time management behaviors of the freshmen students in the CMGT 100 class are below that of the more experienced sophomore and junior students.

Weekly Time Management Summary Data and Findings

In addition to the TM assignments, each week students completed a weekly re-cap survey to reflect and assess their time management effectiveness from the previous week. Question #2 of this survey asked how many assignments the student failed to turn-in, across all their classes, for the previous week, see Figure 2.

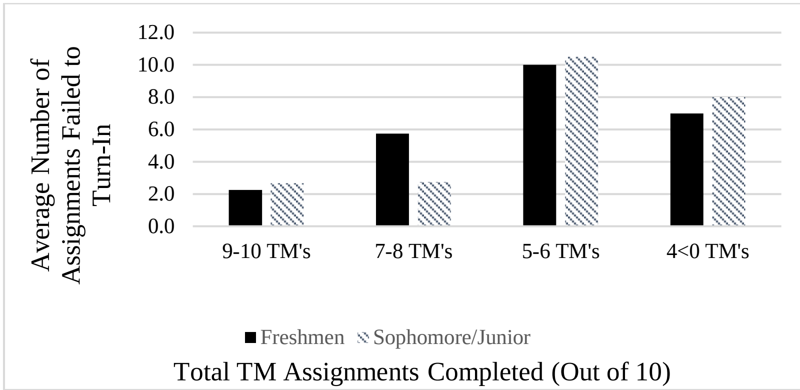

Figure 2: Correlation of total TM assignments completed and average number of assignments failed to turn-in across all classes for freshmen and sophomore/junior students

Generally, across both freshmen and sophomore/junior level students, the data reflects that those students who completed more of the TM assignments averaged much lower incidences of failure in turning in assignments across all their classes. Students who completed 9 to 10 of the TM assignments, reported missing an average of 2.3 (freshmen) and 2.7 (sophomore/junior) per week. Students who completed between 7 to 8 of the 10 TM assignments, reported missing on average 5.8 (freshmen) and 2.8 (sophomore/junior) assignments per week. Students who completed 5 to 6 TM assignments reported missing on average 10.0 (freshmen) and 10.5 (sophomore/junior) assignments per week. Students who completed less than 4 TM assignments reported missing on average 7.0 (freshmen) and 8.0 (sophomore/junior) assignments per week. Overall, those students who consistently completed the TM assignments had fewer instances of failing to turn-in assignments across all their classes. The freshmen students who consistently completed the TM assignments benefited the most. Freshmen who completed between 9 to 10 of these TM assignments averaged the lowest rate of missed assignments. However, the failure rate jumped from an average of 2.3 to 5.8 missed assignments per week when freshmen students only completed 7 to 8 of the TM assignments. This demonstrates a need for these freshmen students to consistently complete these TM assignments to achieve a significant realized benefit.

Post-Survey Data and Findings

After the 10-week implementation of the TM assignments, all 31 students completed the post-survey to assess their overall experience and for the instructor to solicit feedback. The data was separated to differentiate the results of the freshmen (F) students versus that of the sophomore and junior (S/J) students, see Table 2.

For Question #1, 66% (freshmen) and 59% (sophomore/junior) students either strongly agreed or agreed that they plan to implement a system similar to the TM activities, with mean values of 3.9 (freshmen) and 3.8 (sophomore/junior). This demonstrates both groups of students saw the value in the TM activities. For Question # 2, 66% (freshmen) and 44% (soph./junior) either strongly agreed or agreed that the TM assignments improved their academic performance, with mean values of 4.0 (freshmen) and 3.5 (sophomore/junior). This data indicates a higher percentage of freshmen students felt the TM assignments improved their academic performance in comparison to the sophomore/junior level students. For Question #3, 44% (freshmen) and 36% (soph./junior) either strongly agreed or agreed they would have missed more assignment deadlines without the TM activities, with mean values of 3.4 (freshmen) and 3.0 (soph./junior). A slightly higher percentage of freshmen believe the TM assignments improved their performance in completing assignments across all their classes, in comparison to the more experienced sophomore/junior students.

Table 2

Post-Survey question and student response distribution

Question	**Student Responses**					
	SA	**A**	**N**	**D**	**SD**	**Mean**
I plan to implement a system similar to the TM activities	33%(F) 27%(S/J)	33%(F) 32%(S/J)	23%(F) 36%(S/J)	11%(F) 5%(S/J)	0%(F) 0%(S/J)	3.9(F) 3.8(S/J)
The TM activities improved my academic performance	44%(F) 23%(S/J)	22%(F) 27%(S/J)	23%(F) 32%(S/J)	11%(F) 9%(S/J)	0%(F) 9%(S/J)	4.0(F) 3.5(S/J)
I would have missed more assignment deadlines without the TM activities	22%(F) 18%(S/J)	22%(F) 18%(S/J)	45%(F) 27%(S/J)	0%(F) 23%(S/J)	11%(F) 14%(S/J)	3.4(F) 3.0(S/J)

The post-survey also solicited open-ended feedback from the students. The first of the open-ended questions asked the following: "What worked well and was beneficial from the TM activities?" The responses were coded, which grouped similar responses together, in order to summarize and graph the results, see Figure 3. The data from Figure 3 indicates 67% (freshmen) and 73% (soph./junior) of students affirmed the biggest benefit of the TM activities was the fact the students were required to look ahead and identify all their assignments and due dates for the upcoming week. This was the biggest perceived benefit by both student groups. Another 22% (freshmen) and 9% (soph./junior) of students confirmed the TM assignments contributed to improved planning of time commitments, while 11% (freshmen) and 5% (soph./junior) indicated the assignments resulted in completing their coursework sooner than typical. There were a select few sophomore and junior comments that were not relevant and thus not coded, which is why the soph./junior responses do not total 100%.

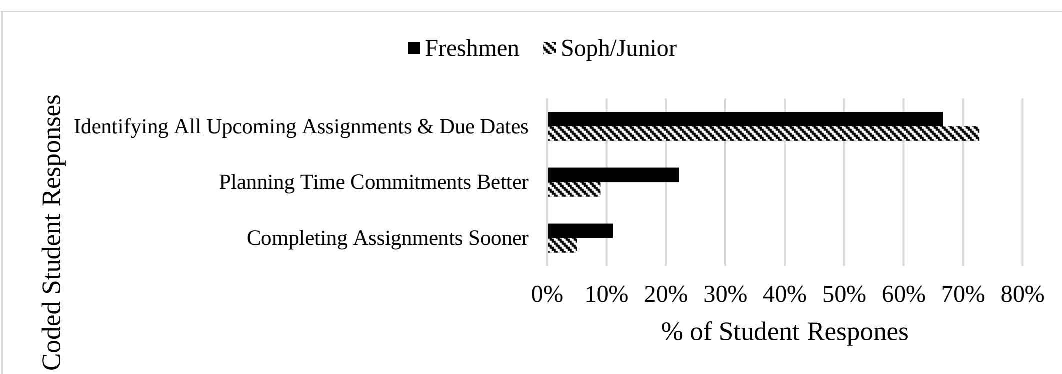

Figure 3: "What worked well and was beneficial from the TM activities?" - Distribution of similar (coded) student responses

The post-survey also asked: “What didn’t work well for you or was a problem with the weekly TM activities?” Figure 4 shows the coded responses with 56% (freshmen) and 23% (soph./junior) students commenting they had trouble remembering to complete and submit the TM activities. To these students the TM activities represented another assignment, which they needed to track, complete and turn-in. Additionally, 33% (freshmen) and 23% (soph./junior) wouldn’t refer back to that plan they created for the week. This would greatly reduce the effectiveness of the TM assignment. Lastly, another 11% (freshmen) and 9% (soph./junior) of respondents didn’t prefer the format of the TM template provided by the instructor. There were a select few sophomore and junior comments that were not relevant and thus not coded, which is why the soph./junior responses do not total 100%.

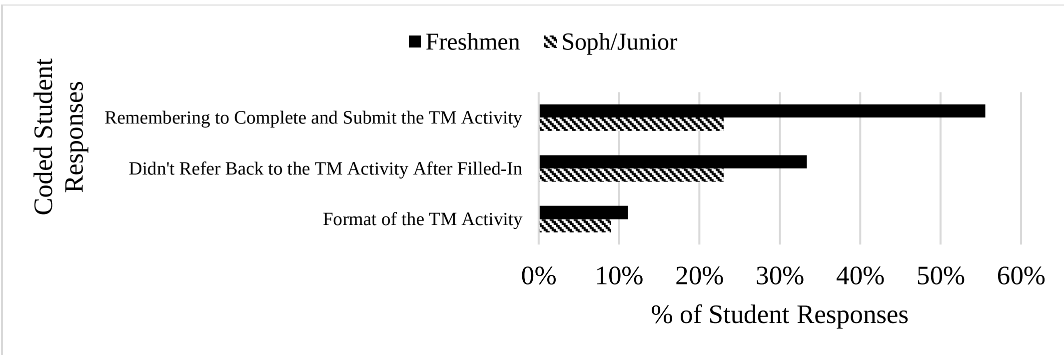

Figure 4: “What didn’t work well for you or was a problem with the weekly TM activities?”- Distribution of similar (coded) student responses

Summary and Conclusion

The first-year attending a four-year university is the most critical time in determining the likelihood a student will persist with their degree. These students are thrust into a situation where they are solely responsible for managing the various demands on their time. Construction students face additional challenges persisting, given their personality tendencies. A series of time management modules were implemented in CMGT 100 in hopes to improve the academic performance of freshmen construction students. Students followed the best practices of a time management practice by: identifying upcoming assignments, listing the due dates, prioritizing completing each assignment, and subsequently reflecting on their effectiveness each week. The TM activities did have shortcomings; students felt it increased their workload as it was another assignment to track and complete, however; overall the results from the TM activities were promising. While freshmen students were the target subjects of this study, both freshmen and sophomore/junior students who consistently completed the TM assignments demonstrated lower instances of failing to turn-in assignments across all their classes. Both sets of student groups also benefitted in that the time management assignments required them to look ahead and identify each of the assignments due for the upcoming week. Additionally, a majority of both student groups planned to implement a similar time management system as they progress towards degree completion. Given the realized improvement in student performance and the perceived benefits by these student groups, construction faculty should be encouraged to implement similar time management trainings into entry level construction classes for the benefit of the students.

References

Adams, R., and Blair, E., (2019) The impact of time management behaviors on undergraduate engineering students' performance. *SAGE Open, 9,* 1-11.

Bernold, L.E. (2007). Preparedness of engineering freshman to inquiry-based learning. *Journal of Professional Issues in Engineering Education and Practice, 133*, 99-106.

Bradley, S., and Bradley, W., (2004, June), Increasing retention by incorporating time management and study skills into a freshman engineering course, Paper presented at 2004 Annual Conference, Salt Lake City, Utah

Hanson, M. (June 17, 2022). College dropout rates. Retrieved from https://educationdata.org/college-dropout-rates.

Häfner, A., Stock, A., Pinneker, L., and Ströhle, S., (2013). Stress prevention through a time management training intervention: an experimental study, *Educational Psychology: An International Journal of Experimental Educational Psychology*, *34*(3), pp. 403-416

Kader, A., and Eissa, M., (2015). The effectiveness of Time Management Strategies Instruction on students' academic time management and academic self-efficacy. *International Journal of Psycho-Educational Sciences*. *4*(1), 43-50.

Lee, N., Ponton, R., Jeffreys, A.W., Cohn, R. (2011). Analysis of industry trends for improving undergraduate curriculum in construction management education. *ASC Proceedings of the 47th Annual International Conference*, Omaha, NE.

Macan, T. H., Shahani, C., Dipboye, R. L., & Phillips, A. P. (1990). College students' time management: Correlations with academic performance and stress. *Journal of Educational Psychology*, *82*(4), 760–768.

MacCann, C., Fogarty, G., and Roberts, R. (2012). Strategies for success in education: Time management is more important for part-time than full-time community college students, *Learning and Individual Differences*, *22*(5), pp. 618-623

Maloshonok, N., and Terentev, E. (2017). The mismatch between student educational expectations and realities: prevalence, causes, and consequences, *European Journal of Higher Education*, *7*(4), pp. 1-17

McFarland, J., Hussar, B., de Brey, C., Snyder, T., Wang, X., Wilkinson-Flicker, S., Gebrekristos, S., Zhang, J., Rathbun, A., Barmer, A., Bullock Mann, F., and Hinz, S. (2017). The Condition of Education 2017 (NCES 2017- 144). U.S. Department of Education. Washington, DC: National Center for Education Statistics. Retrieved from https://nces.ed.gov/pubsearch/pubsinfo.asp?pubid=2017144

Meer, J., Jansen, E., and Marjolein, T. (2010). "It's Almost a Mindset That Teachers Need to Change": first-year students' need to be inducted into time management. *Studies in Higher Education*. *35*(7), pp. 777 - 791

Mills, T., Novak, V., and Danforth, H., (2012). First-Year Experience in Construction Education. *48th ASC Annual International Conference Proceedings.*

Statement to Address Reviewers' Comments

Dear respected reviewers,

The following changes and edits have been made to the submitted manuscript tilted "Development of Formal Constructability Review Meeting Guidelines for Transportation Agencies" to address reviewer comments:

1. Papers targeted to the transportation literatures are added. This includes papers for current practices and constructability review procedures on different State DOTs including Arizona, Florida, Kentucky, Louisiana, North Carolina, Texas, Washington, and Wisconsin.

2. Additional manuals of practice relevant to constructability review process are added to the manuscript. Currently manuals includes: AASHTO, Construction Industry Institute, and the American Society of Civil Engineers, Transportation Research Board (TRB) guidelines, and the Federal Highway Administration (FHWA).

3. A list of the main questions discussed during DOT and construction industry professional interviews is added to the manuscript.

4. Figure #1 is revised (citation added).

5. The assessment process for CR meetings efficiency is added to the revised manuscript. A brief example of how assessment is conducted by NCDOT (using the research outcomes) is provided. Full example is not included due to the page limitation.

6. The contradiction between abstract and conclusion about the timing of constructability review meeting is corrected.

7. The redundancy resulting in confusion about how many CR meeting is conducted by different DOTs (no meeting vs. single or multiple meetings) is eliminated.

8. Paper structure, format, and grammar were revised.

Development of Formal Constructability Review Meeting Guidelines for Transportation Agencies

Constructability reviews have been used by multiple departments of transportation (DOTs) in the United States for more than a decade to enhance the project design documents by introducing construction knowledge to the design process. Constructability reviews provide the contractors with a complete set of bid documents that have a reduced possibility of encountering any obstacles during project construction phase. The main objective of this research is to provide DOTs and transportation agencies with guidelines to conduct formal constructability review meetings with increased efficiency. Transportation agency personnel, consultants, and contractors were interviewed to collect data relevant to constructability review meetings best practices, advantages, and disadvantages. The analysis of interviews results determined that conducting constructability review meetings before 50% completion of the design phase is recommended. A successful meeting should include project designer, project manager, and a minimum of 3 general contractors. Attendees should receive advanced information regarding the project, and meetings should be held in the construction site to ensure proper communication. The implementation of the research outcomes will increase the constructability review meeting outcomes, minimize cost and schedule overruns, and enhance the overall safety of the construction project.

Key Words: Constructability, Buildability, Constructability Review, Cost Overrun, Schedule Overrun, DOTs

Introduction

The concept of "constructability" in the United States, or buildability in the United Kingdom emerged in the early 1980s. Constructability concept evolved to increase the economic feasibility of construction projects, and maintain construction quality and affordability (Uhlik and Lores, 1998). According to the Construction Industry Institute (CII), constructability is defined as "the optimum use of construction knowledge and experience in planning, design, procurement, and field operations to achieve overall project objectives," (CII 1986). Similarly, constructability is defined as "a project property that reflects the ease with which a project can be built and the quality of its construction documents," (Dunston et al., 2003). Various definitions evolved for the term "constructability" according to the project specific conditions, including the following definitions:

- "A measure of the ease or expediency with which a facility can be constructed," (Hugo et al., 1990)
- "The integration of construction knowledge, resources, technology, and experience into the engineering and design of a project," (Anderson et al., 1995)
- "The capability of being constructed," (ASCE, 1991)
- "A Process that utilizes construction personnel with extensive construction knowledge early in the design stages of projects to ensure that the projects are buildable, cost-effective, biddable, and maintainable," (AASHTO, 2000)

In an attempt to improve project constructability, transportation agencies implemented different measures including peer review of design documents, brain storming sessions, the use of different commercial software packages to improve project coordination (Meadati et al., 2011 and 2012), the use of design checklists, implementing artificial intelligence (AI) in constructability evaluation (Xiao et al., 2018), and conducting constructability review meeting(s) to discuss project constructability (Bonilla et al., 2022, Akhnoukh et al., 2022). In the past decade, departments of transportation (DOTs) and transportation agencies have widely attempted to implement constructability review meetings during different stages of project design stage. However, most constructability review meetings lack formal procedures and outcomes assessment.

Literature Review

The increased complexity of construction projects, and the budget constraints encouraged transportation agencies to optimize the use of their limited resources to maintain the conditions of national infrastructure projects. Decades ago, several research programs investigated the possible of developing durable construction materials to increase the life span of construction projects and minimize the need to maintenance, repairs, and replacement of deteriorated infrastructure projects (Akhnoukh, 2018, 2010). As a result, new materials with superior characteristics were introduced to the local construction market including high grade steel, ultra-high-performance concrete, and large-size prestress strands). Different research programs investigated the reliability of infrastructure projects (Morcous and Akhnoukh, 2007) and modeled infrastructure deterioration (Morcous and Akhnoukh, 2006). The research findings were used by transportation agencies increased ability to prioritize the use of their limited resources to maintain infrastructure projects in operating conditions. Recently, DOTs introduced the constructability reviews concept during project design phase to possibly predict any future site issues that may evolve during construction phase. Early detection of construction issues will significantly reduce the project expenditure, reduce cost and schedule overruns, and enhance project safety. During the last 10 years, different DOTs in California, New York, Indiana, North Carolina, Washington, Florida, and Tennessee started to conduct constructability reviews through formal meetings, held in construction site during the project design phase.

Constructability reviews requires a champion to ensure successful implementation. Traditionally, the construction project manager assume the champion role and guide project stakeholders during the meetings designated time.

The main role of the construction project manager is to provide a detailed review of the draft construction plans and specifications. This review, referred to as constructability review, results in improved plans and eliminate multiple problems during different phases of construction. The constructability review meetings provide different stakeholders involved in the construction process including the owner, designer, contractor, and project manager with a detailed process to share their expertise and knowledge to improve the workflow and efficiency of the construction process, while being at the design phase (Gambatese et al., 2012).

In research conducted by Washington State DOT, researchers investigated the possible advantages attained by formal constructability review meetings. The research outcomes provided the DOT personnel with outlines to conduct successful meetings, and a framework to increase the constructability review meetings efficiency (McManus et al., 1996). In a different study, projects executed after incorporating formal constructability review meetings were compared to similar projects where constructability review meetings were ignored. The research study showed that the constructability reviews resulted in significant improvement in project workflow; the benefit/cost ratio of constructability reviews is greater than 2.0 (Dunston et al., 2002). Similar research showed that the effectiveness of constructability review meetings is significantly increased when they are tailored to the project specific conditions. Thus, constructability review process has to be flexible to accommodate different projects (Stamatiadis and Hartman, 2011). The Kentucky Transportation Cabinet (KYTC) has incorporated the constructability review concept in their projects during design phase. The KYTC meetings are performed by four reviewers. However, these meetings represented more of an ad hoc approach which lacked the systematic approach in identifying key-problems and challenges to the project constructability (Stamatiadis, 2013) Similarly, the Florida Department of Transportation (FDOT) has developed formal constructability review procedures for highway construction projects. FDOT constructability review program depends on the utilization of standard checklist during CR meetings (Ellis et al., 1992). Arizona Department of Transportation (ADOT) has developed detailed guidelines on how to conduct a formal CR meeting, record, and implement the recommendations (Wright, 1994). The Wisconsin Department of Transportation (WDOT) investigated the constructability concepts and developed its tools for constructability Implementation in highway construction (Russel and Swiggum, 1994). Louisiana Department of Transportation conducted recent research that showed it may be beneficial to State DOTs to conduct CR meetings and discuss constructability issue regardless of the nature of the project, project delivery, and the portion of the project that may be outsourced. The Louisiana DOT project specified the main important dimensions to be considered in highway construction project management. These project management dimensions are to be articulated in constructability review meetings to ensure project successful implementation. There dimensions include time management, cost management, quality control, project environmental aspects, value engineering, workforce qualifications, project delivery methods, and operation and maintenance (Jafari et al., 2019). In relevant research, the impediments to conducting successful formal constructability review meetings were investigated. The research outcomes showed that staffing and budgetary constraints represent a major challenge that limits the abilities of transportation agencies in conducting formal constructability review meetings for all projects conducted. However, the research findings concluded that formally conducted meeting during early design phase results in 1.25% of project budget savings (Stamatiadis et al., 2017). Thus, the implementation of formal CR in projects with high budget will result in significant cost savings.

The influence of constructability review meetings on budget savings is evaluated according to the time the CR meeting is conducted. The research outcomes showed that budget savings is maximized when project CR process is implemented at early stages of the construction project design phase, as shown in Figure 1.

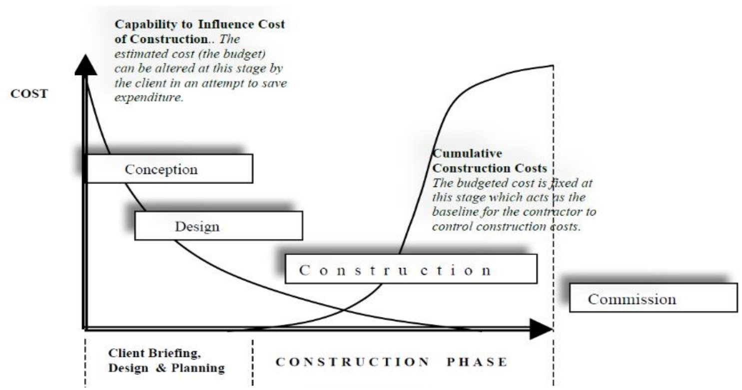

Figure 1. Influence of constructability review meetings on project budget vs. project phase (bahaudin et al., 2012)

Objectives and Methodology

The main objective of this research is to provide DOTs and transportation agencies with guidelines to conduct formal constructability review meetings with increased efficiency, and highlight possible parameters to be used in the assessment of constructability review meetings outcomes. The research objectives are attained through the following methodology:

- Conduct interviews with DOT personnel at different states to receive feedback regarding their constructability review meetings practices. Feedback focused on the timing of constructability review meetings, invited project stakeholders and their expertise, the nature of the projects where constructability review meetings are applicable, meetings' location and duration, the main challenges faced by DOT personnel when meetings are conducted, and the possible project parameters to be used in meetings outcomes assessment.
- Developed a questionnaire to survey construction professionals at the State of North Carolina. The questionnaire surveyed the recommendations to formalize successful meetings for future transportation projects within the State. Thirty-five interviews were held, the list of interviewees included 19 NCDOT personnel and 16 general and specialty contractors. The questionnaire was handled through web meetings, phone interviews, and through 6 different on-site constructability review meetings attended by the research team. The following list of questions was included in DOTs and North Carolina construction professionals survey:

    - Does your DOT project require CR?
    - If CR and CR meetings are optional, what are the indicators that a CR meeting is required for a given project?
    - What type of CR meetings do you implement (formal or non-formal)?
    - At what phase of project design do you conduct your CR meetings?
    - Who are the project stakeholders invited to CR meetings?
    - What are the parameters used to assess the efficiency of your CR process?
    - Do you have a specific suggestion for the CR meeting invitation? Number of invitees? Invitee background?

The research team compiled the data received from the questionnaire and DOT interviews to provide transportation agencies with recommendations to conduct efficient formal constructability review meetings, and provide guidelines to assist DOT personnel in optimizing project constructability, avoiding cost and schedule overruns. Detailed outcomes are shown in the following sections.

Research Findings

Departments of Transportation Interviews

State DOTs started to implement different forms of constructability reviews; 35% of interviewed DOTs stated that they conduct constructability review meetings, 55% conduct reviews using checklists, peer revisions, feedback from experts, or through self-revisions; and 10% of surveyed DOTs do not implement constructability reviews in their projects. Constructability review meetings implemented by DOTs are either formally conducted according to predetermined guidelines (52%) or informally (48%). Typically, DOTs plan on conducting constructability review meetings during the design phase to ensure the early detection of constructability issues. The type of constructability reviews and timing for constructability review meetings is shown in Figure 2.

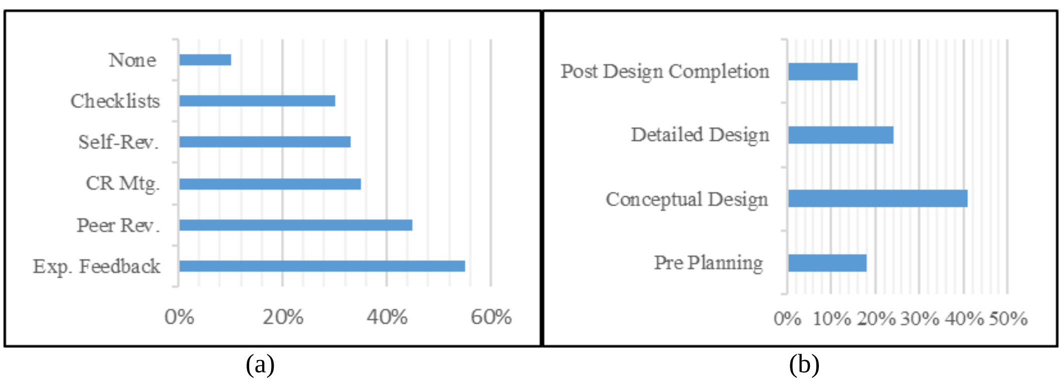

Figure 2. (a) Type of constructability review (b) Timing of constructability review meeting

Stakeholders invited to attend constructability reviews for DOT projects includes DOT construction personnel, design personnel, maintenance staff, external contractors, and other professionals including utility companies' personnel, material suppliers, and environmental experts. Percentage of attendees according to their professional background is shown in Figure 3.

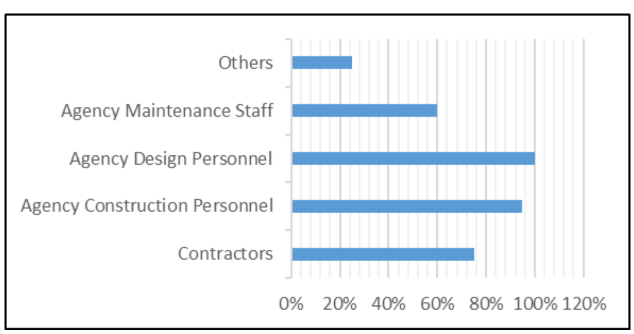

Figure 3. Constructability review meetings attendees according to their professional background

Constructability review meetings could potentially be implemented in any DOT project regardless to the project type, budget, duration, or site conditions. However, constructability review meetings are challenging due to coordination problems, time consuming, and cost associated by conducting on-site meetings. While some states requires constructability review meetings for all projects, other state DOTs restrict the implementation of meetings to specific project types, as shown in Figure 4.

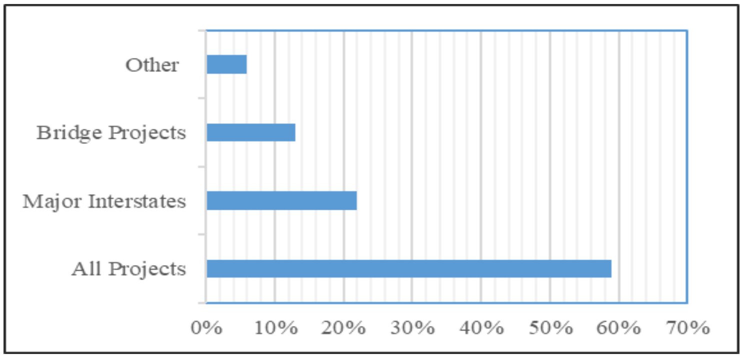

Figure 4. Type of construction projects for constructability review meeting implementation

Constructability reviews in general, and constructability review meetings in particular, provide DOTs and other transportation agencies with the opportunity to predict potential construction projects prior to project execution. The efficiency of constructability review meetings and their outcomes are hard to quantify. DOTs use different approaches to assess meetings outcomes. Constructability review assessment parameters and their corresponding application by different DOTs are shown in Figure 5.

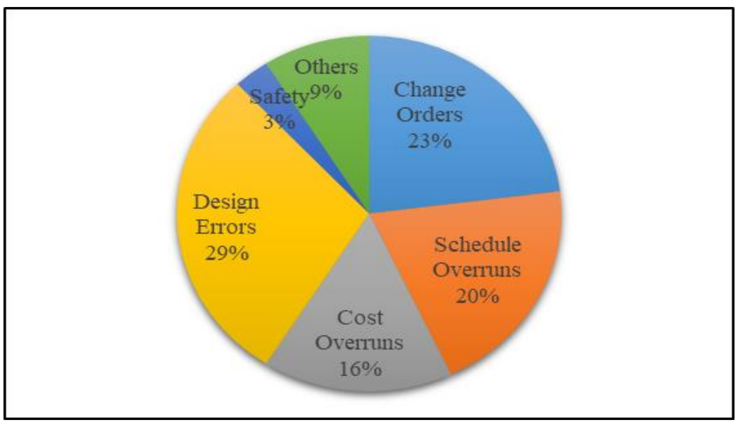

Figure 5. Constructability review meetings assessment parameters

NCDOT Personnel and Contractors Questionnaire

The research team developed a questionnaire to collect feedback to assist in conducting sufficient constructability review meetings at the State of North Carolina. The questionnaire was prepared in light of DOT survey feedback. Thirty-five questionnaire responses were recorded, including 19 responders from NCDOT personnel, and 16 local contractors. According to the feedback provided by the responses, the following suggestions, shown in Table 1, were made regarding future constructability meetings attendance.

Table 1.

Suggestions for future constructability review meetings participation

Suggested Participants	**Responses**	**Percentage**
At least 3 contractors	5	14.2%
No more than 15 attendees	4	11.3%
Number of participants should vary according to project complexity	3	8.6%
Maintenance Personnel	1	2.9%
Utility company representatives	2	5.8%
Subcontractors	1	2.9%
No limit on attendees (for successful brainstorming)	1	2.9%
Traffic Management Personnel	1	2.9%
Roadway Personnel	1	2.9%
No Suggestions	16	45.6%

The questionnaire responses suggested that on-site constructability reviews are preferred for increased efficiency. Constructability review meeting duration should range from 2.0 to 4.0 hours to allow for sufficient discussions. According to the feedback obtained, A slight majority of the responders preferred having multiple meetings for constructability reviews to be held prior to the completion of 50% of the design phase, as shown in Table 2.

Table 2.

Constructability review meetings implementation timing

Design Phase Percentage	Multiple Reviews Needed		One Review Needed	
	NCDOT	Contractors	NCDOT	Contractors
20-30%	5	4	4	7
30-40%	0	0	0	0
40-50%	2	2	0	1
50-60%	0	0	1	1
60-70%	6	2	3	2
70-80%	1	0	0	1

NCDO personnel and contractors interviewed have indicated that review meetings are faced with obstacles, and could be cancelled or delayed due to different factors including the absence of constructability champions, participants might not be well prepared for constructability review meetings due to lack of coordination, and work schedule constraints. Finally, contractors raised concerns regarding the financial burdens incurred due to meeting attendance, specially for remote on-site meetings.

Assessment of Constructability Review Meeting Outcomes

The assessment of CR meetings efficiency is challenging due to the inability to quantify the losses avoided due to CR implementation. The following 3 parameters are identified in the DOT practices survey and construction professional questionnaire feedback: 1) project safety, 2) construction quality, and 3) schedule compliance. The contribution of the CR meeting on the afore-mentioned parameters is evaluated on a scale of through 4, according to Table 3 (a). Project bid items are evaluated using the criteria listed in Table 3(a) to assess the overall impact of the CR on different project activities, as shown in Table 3(b).

Table 3.

(a) Impact scale of project CR, and (b) Assessment of CR total impact on bid items

3(a) 3(b)

Individual Assessment Scale	Impact Scale	Assessment of Total Impact	
1	No Impact	3-5	Low
2	Minimal	6-8	Minimal
3	Moderate	9-10	Moderate
4	High	11-12	High

CR meeting assessment tool is implemented by NCDOT in recent highway construction project. The outcomes of the assessment criteria for a small component of the project (detour construction) is shown in Table 4.

Table 4.

Assessment of overall impact of CR on NCDOT construction project

	Items Description	Safety	Quality	Schedule	Overall
Bid Item List	Detour signing	4	2	3	9
	Snow Plowable Pavement Markers	4	1	1	6
	Pavement Marking	4	1	1	6
	Temporary Pavement Markings	4	1	1	6

Conclusions

The outcomes of this research project shows that transportation agencies and DOTs are increasing implemented constructability review for their construction projects. The implementation of constructability reviews through formal meetings with predetermined guidelines is favored by 35% of interviewed DOTs. Constructability review meetings held at early stages of project design phase is advantageous due to the ease of revising the project design. Interviews conducted for North Carolina contractors and DOT personnel show that conducting constructability review meetings prior to 50% design completion is suggested by slight majority of interviewees. Suggested participants includes project managers, consultants, general and specialty contractors, maintenance and utility personnel. The advantages of constructability reviews include cost and time savings, reducing the number of claims and change orders, and improved site safety. Despite their advantages, several DOTs doesn’t implement formal constructability review meetings. The major impediments to the meetings implementations includes the lack of funding, hardships in scheduling meetings, and the inability to coordinate concurrent site visits for sufficient number of participants. The assessment of constructability reviews outcomes presents a major challenge. However, the research findings suggests that constructability review effectiveness may be quantified by estimating projects compliance to budget and schedule or reduced OSHA citations for projects where constructability reviews are implemented in comparison to comparable projects that ignored constructability reviews. The implementation of the research findings according to would assist transportation agencies and DOTs in formalizing constructability review meetings and increase meetings efficiency for transportation projects.

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References

AASHTO, "Constructability review best practice guide," American Association of State Highway and Transportation Officials, Washington, D.C., 2000

Akhnoukh, A.K., "Implementation of nanotechnology in improving the environmental compliance of construction projects in the United States," Particulate Science and Technology Journal, Vol. 36, No. 3, 2018, pp. 357-361

Akhnoukh, A.K., "Overview of nanotechnology applications in construction industry in the United States," Journal of Micro and Nano-systems, Vol. 5, No. 2, 2013, pp. 147-153

Akhnoukh, A.K., Bonilla, M., Norboge, N., Findley, D., Rasdorf, W., and Fullerton, C., "Evaluating the efficiency of constructability review meetings for highway department projects," Proceedings of the International Road Federation World Meeting & Exhibition, Dubai, UAE, 2022

ASCE," Constructability and constructability programs: white paper," American Society of Civil Engineers Journal of Construction Engineering and Management, Construction Management Committee, Vol. 117, No. 1, 1991, pp. 67-89

Anderson, S.D., Fisher, D.J., and Gupta, V.K., "Total constructability management: a process-oriented framework," Project Management Journal, Vol. 3, 1995, pp. 3-11

Bahaudin, A.Y., Elias, E.M., Dahlan, H., and Jamaluddin, R., "Construction cost control: a review of practice in Malaysia," Proceedings of the 3rd International Conference on technology and Operation Management, Indonesia, 2012

Bonilla, M., Rasdorf, W., Akhnoukh, A.K., Norboge, N., Findley, D., and Fullerton, C., "Critical constructability review indicators for construction of transportation infrastructure," Construction Research Congress (CRC), 2022

CII, "Constructability – a primer," Construction Industry Institute (CII) Publication 3-1, Austin, Texas, 1986

Dunston, P.S., McManus, J.F., and Gambatese, J.A., "Cost/Benefits of constructability reviews," NCHRP Project 20-07, Task 124, TRB, Washington, D.C., 2002

Ellis, R.D., Kumar, A., and Ahmed, Q.A., "Life cycle re-constructability: final report," Engineering and Industrial Experiment Station, University of Florida, Gainesville, Florida, 1992

Gambatese, J., Pocock, J., and Phillip, D., "Constructability review process for transportation facilities workbook," NCHRP Report 390, Transportation Research Board, Washington, D.C., 1997

Hugo, F., O'Connor, J.T., and Ward, W.V., "Highway constructability guide," Center for Transportation Research, University of Texas at Austin, Austin, Texas, Research Project 3-6-88-1149, 1990

Jafari, A., Kermanshachi, S., Safapour, E., and Taghinezhad, A., "Synthesis on the best practices for State DOTs to determine project delivery time, project management, and ratio of consultant to in-house design," Report No. FHWA/LA.17/633, 2019

McManus, J.F., Phillip, N.A., Stanton, J.F., and Turkiyyah, G.M., "A framework for the constructability review of transportation projects," Seattle, WA: Washington State Transportation Center (TRAC), 1996

Meadati, P., Javier, J., and Akhnoukh, A.K., "Building information modeling implementation- current and desired status," Computing in Civil Engineering, Vol. 63, No. 416, 2011, pp. 512-519

Meadati, P., Liou, F., Irizarry, J., and Akhnoukh, A.K., "Enhancing visual learning in construction education using BIM," International Journal of Polytechnic Studies, Vol. 1, No. 2, 2012

Morcous, G., and Akhnoukh, A.K., "Reliability analysis of NU girders designed using AASHTO LRFD," Proceedings of the ASCE Structures Congress, Long Beach, California, 2007

Morcous, G., and Akhnoukh, A.K., "Stochastic modeling of infrastructure deterioration: an application to concrete bridge decks," Proceedings of the Joint International Conference on Computing and Decision Making in Civil and Building Engineering, Montreal, Canada, 2006

Russel, J.S., and Swiggum, K.E., "Investigation of constructability concepts and tools of highway construction," Tech Report No. 115, Construction Engineering and Management Program, University of Wisconsin-Madison, Madison, WI, 1994

Stamatiadis, N., Sturgill, R., Goodrum, P., Shocklee, E., and Wang, C., "Tools for applying constructability concepts to project development (design)-final report," Kentucky Transportation Research Center Report KTC-13-14, 2013

Uhlik, F.T., and Lores, G.V., "Assessment of constructability practices among general contractors," ASCE Journal of Architectural Engineering, Vol. 130, No. 5, 1998, pp. 656-669

Wright, E.D., "Constructability Guide," Arizona Department of Transportation (ADOT), AZ, 1994

Xiao, C., Liu, Y., and Akhnoukh, A.K., "Bibliometric review of artificial intelligence (AI) in construction engineering and management," Proceedings of the ASCE International Conference on Construction and Real Estate Management, South Carolina, 2018

Faculty Advisors' Perspectives on the Current State of Construction Honor Societies

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The Sigma Lambda Chi International Construction Honor Society (SLC) is the only honor society associated with construction management. A few research studies have been published regarding the benefits, criteria, and motivations of joining an honor society, however, no research has been conducted specifically related to the honor society in the field of construction. This paper summarizes the results of a survey conducted to find out the opinions of SLC chapter advisors on how they perceive multiple factors related to student outcomes, the impact of the pandemic on SLC chapter operations, and both internal and external support for their respective SLC chapters. The outcomes revealed several interesting results regarding the benefits, obstacles, and motivations of advising a Sigma Lambda Chi chapter. The results of this study can help to understand the impact of the pandemic on SLC chapter operations. SLC faculty advisors can have a better understanding of their colleagues' perspectives, and SLC International Directors and Officers can use the results of this study to help to establish new SLC chapters and to be more supportive of existing SLC chapters and their faculty advisors.

Key Words: Honor Society, Sigma Lambda Chi, Faculty Advisor, Pandemic Impact

Introduction

An honor society is "an association of primarily collegiate chapters whose purposes are to recognize and encourage high scholarship and/or leadership achievement in some broad or specialized field of study", according to the Association of College Honor Societies' definition (ACHS, 2022). College honor societies began as social clubs that included activities such as drinking alcohol and discussing literature. The precursor to college honor societies was the social and literary fraternity Phi Beta Kappa formed at the College of William and Mary in 1776. This led to other similar groups eventually forming honor societies and fraternities that served specific academic disciplines with more formal requirements. Phi Beta Kappa finally became the first honor society for liberal arts and sciences in 1898. The field of engineering established Tau Beta Pi and the field of scientific research formed Sigma Xi in the 1880s (Watkins & Ostin, 2018).

The Sigma Lambda Chi International Construction Honor Society (SLC) is the only honor society associated with construction management. The first chapter of SLC, Alpha Chapter, was established on April 30, 1949, by a group of people from Michigan State University (SLC, 2022). SLC has grown to include 90 chapters across the United States and Australia, and 73 of them are currently active. SLC is a member of the Association of College Honor Societies (ACHS) which is the leading certifying body for honor societies (ACHS, 2022).

A few research studies have been published regarding the benefits, criteria, and motivations of joining an honor society. Watkins and Ostin (2018) studied the commonalities among Engineering Honor Societies, the possible roles of an honor society within an engineering department, and some best practices for effective honor society chapters. They found that the most effective honor society chapters recognize students' academic achievement and provide opportunities for networking, community outreach, and service. Ferrari et al. (2006) studied academic honor society alumni's education and employment experiences, comparing the responses from honor society leaders and non-leaders in the field of psychology. Gauer and Jackson (2017) developed a study to determine the association between the Medical College Admission Test and acceptance to Alpha Omega Alpha Medical Honors Society. Hopkins et al. (2015) explored the key technology design considerations for creating a virtual nursing honor society. They developed another student to explore honor society membership retention strategies in the field of nursing (Hopkins et al., 2016). Rosenthal et al. (2009) and Specter et al. (2015) explored the association between membership in an honor society in the medical field and the selection for residency. Hill et at (2022) explore the disparities in medical student membership in honor societies based on students' race, ethnicity, sex, sexual orientation, socioeconomic status, and the intersection of different identities.

The research studies related to academic honor societies are mostly developed in the field of medical science, nursing, psychology, liberal arts, and engineering. However, no research has been conducted specifically related to the honor society in the field of construction. Moreover, like almost all aspects of our lives, the operations of student clubs and honor societies were greatly impacted by the COVID-19 pandemic. With many student chapters going dormant during the pandemic, the way SLC chapters are advised and supported may have shifted for some universities.

To bridge the gap mentioned above and to understand the impact of the pandemic on SLC chapters, this study is developed to gather SLC faculty advisors' perspectives on these issues. The main objectives of this study are to get SLC advisors' opinions on the benefits for students to joining SLC, the impact of the COVID-19 pandemic on SLC chapters, the motivations of becoming SLC advisors, the enablers and inhibitors of having an SLC chapter, and advisors' suggestions on how SLC chapters can be more effective and beneficial to the students. This study will contribute to the body of knowledge by being the first formal study on SLC. The results of this study can help to understand the impact of the pandemic on SLC chapter operations. SLC faculty advisors can have a better understanding of their colleagues' perspectives, and SLC International Directors and Officers can use the results of this study to help to establish new SLC chapters and to be more supportive of existing SLC chapters and their faculty advisors.

Research Method and Data Collection

To fulfill the research objectives mentioned above, a survey is developed and disseminated to gather opinions from SLC faculty advisors. The survey is anonymous and has been reviewed by the Institutional Review Board under protocol #22-1374, which ensures that research projects involving human subjects follow federal regulations. The survey includes four major groups of questions, including demographic information, SLC chapter information, SLC advisor's opinions in Likert scales, and advisor's opinions by text entry. Each group includes several questions, as shown in Table 1.

Table 1

Survey questions

Part I Demographic information	1. Age 2. Gender 3. Academic position 4. Years at current institution 5. Years being an SLC advisor
Part II SLC chapter information	1. Number of induction ceremonies during the past academic year 2021-2022 2. Number of induction ceremonies per academic year before COVID-19 3. Number of inductees to SLC during the past academic year 2021-2022 4. Number of inductees to SLC per academic year before COVID-19
Part III Advisor's perception of having SLC - Likert scale questions	On a scale of 1 to 10 (1 minimal, 10 maximum), how much do you agree with the following statement? 1. Joining SLC helps students to perform better in school. 2. Joining SLC helps students with job placement. 3. Joining SLC motivates students to provide services to local communities. 4. Joining SLC motivates students to become leaders. 5. Joining SLC helps students to communicate better. 6. SLC officers are more likely than their peers to be leaders in other campus organizations.
Part IV Advisor's perception of having SLC – text entry	1. In your opinion, what are the benefits of having an SLC at your institution? 2. In your opinion, what are the obstacles to having an SLC at your institution? 3. What motivates you to be the faculty advisor for SLC? 4. What do you think SLC International can do to support advisors better? 5. What can your Department Chair/Program Leader do better to promote and support SLC student chapters at your institution?

The survey was hosted on Qualtrics and a link to the survey was sent out to 74 current SLC advisors through email. 26 responses were received within three weeks (35% response rate). Out of 26 responses, 22 of them are complete and the complete responses are used in the following results and analysis sessions.

Survey Results and Analysis

The experience and background of survey respondents are diverse in terms of age, gender, academic positions, and years of experience. The demographic information of 22 complete survey respondents is summarized in Figure 1. It shows that 50% of respondents are over 50 years old and the other half are from 31-50 years old. 41% of them are females and 59% of them are males. The results also show that SCL faculty advisors hold different academic positions in their departments. 32% of respondents hold the rank of tenure-track assistant professor positions, 18% of them are associate professors, and 18% of them are full professors. 23% are teaching professors/lecturers, one SLC faculty advisor is an Academic Advisor and another one is an Assistant Dean. As for their years of experience being SLC faculty advisors, 50% of the respondents have been SLC advisors for less than 6 years, and the other half of them have been SLC advisors for more than 6 years.

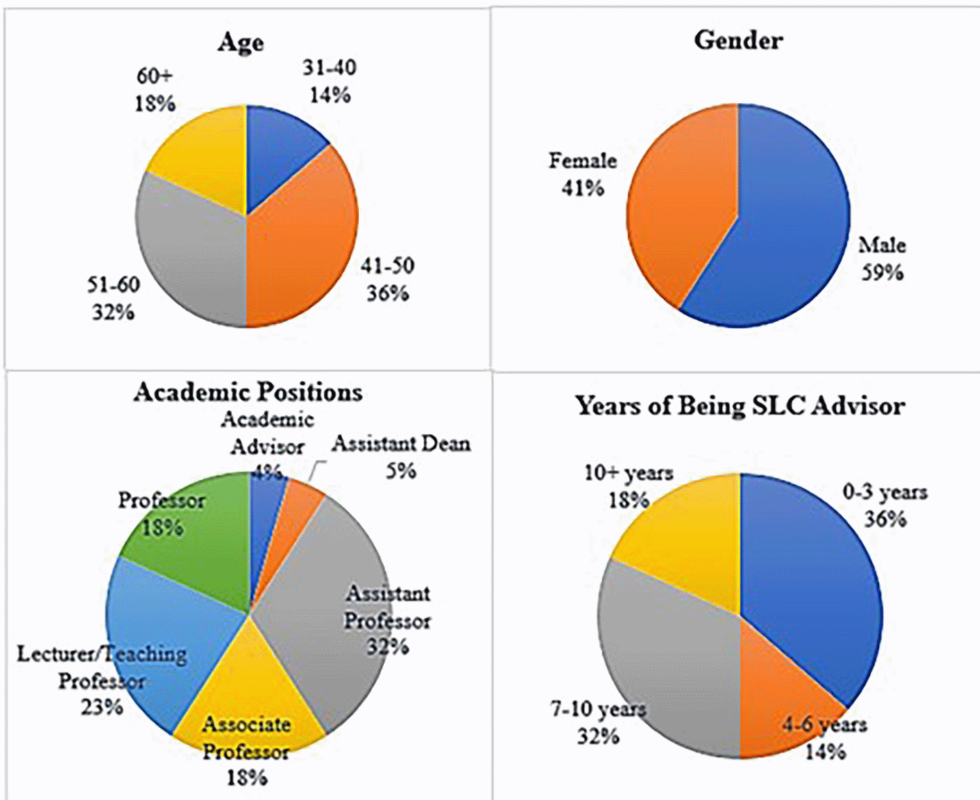

Figure 1. Demographic information of survey respondents

The SLC chapters' situation varies in terms of the number of induction ceremonies and the number of inductees. Figure 2 summarized the information related to chapter induction ceremonies and the number of inductees during the academic year of 2021-2022 and typical numbers before the COVID-19 pandemic. It shows that 5 out of the 22 chapters didn't conduct any induction ceremony during the academic year of 2021-2022, and only 2 chapters reported zero induction ceremonies before the COVID-19 pandemic. 3 chapters did more than 2 induction ceremonies before the COVID-19 pandemic and none of the chapters were able to do that during the year 2021-2022. Figure 2 shows that the COVID-19 pandemic impacted the number of inductees as well. During the year 2021-2022, 14 chapters inducted 0-10 new members, 7 chapters inducted 11-25 new members, and only 1 chapter inducted 25-50 new members. Before the COVID-19 pandemic, 11 chapters inducted 0-10 new members, 8 chapters inducted 11-25 new members, and 3 chapters inducted 25-50 new members each year. Figure 2 indicates that the COVID-19 pandemic negatively impacted the number of induction ceremonies and the number of inductees for the 22 SLC chapters whose faculty advisors responded to this survey.

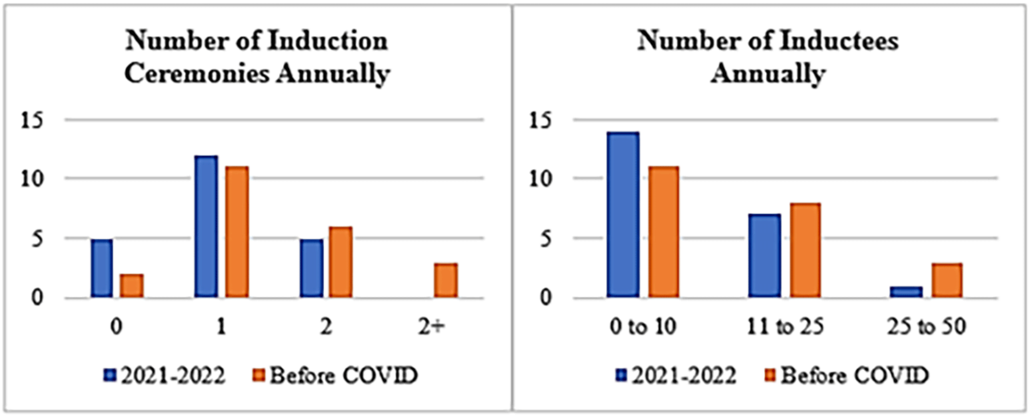

Figure 2. Number of induction ceremonies and inductees before and after the COVID-19 pandemic

The third group of questions is about the SLC faculty advisor's opinions on the benefits for students joining SLC. The results are summarized by the boxplots in Figure 3. A wide range of responses are collected from advisors and for every question, there is someone giving 0 points and another advisor giving 10 points. The number of data points is not large enough to effectively determine outliners so all complete data are included in the results and analysis. The average score, 25th percentile score, and 75th percentile score for SLC members being leaders of campus organizations are higher than other questions' responses, which indicates a stronger association between the two compared to the other benefits. Figure 3 indicates that there is no apparent association between being a member of SLC and their academic performance, job placement, service commitment, being future leaders, and better communication skills. This result is different from what is shown in the literature.

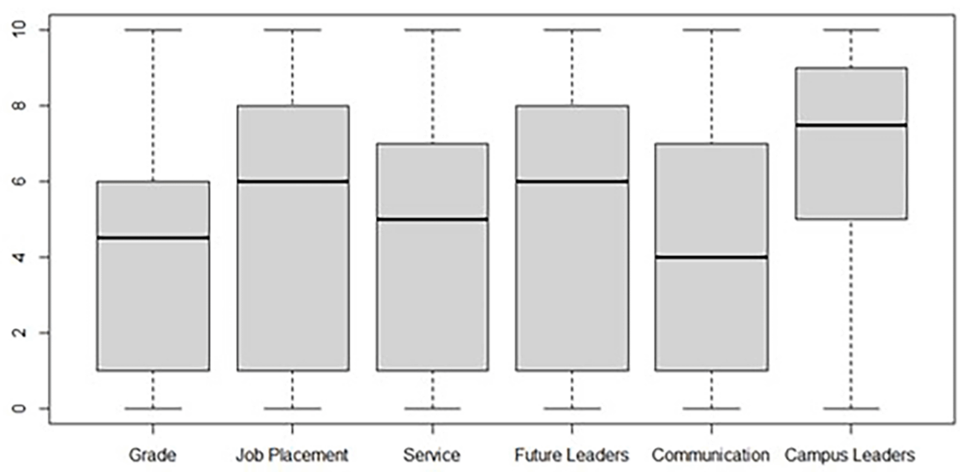

Figure 3. Boxplot of survey responses regarding benefits of joining SLC

The fourth group of questions is about the SLC faculty advisor's perspectives on the current state of SLC and their suggestions. Many advisors answered these text-entry questions, and their responses related to the benefits of having an SLC chapter, the obstacles to having an SLC chapter, their motivations for being an SLC faculty advisor, expectations on support from SLC International, and support from department leaders are summarized in Table 2.

Table 2	
Survey responses related to SLC faculty advisor's perspectives and suggestions	
Benefits of having SLC	• Recognize/distinguish students' achievement and service to the program • A networking opportunity among alumni, industry, and students • Motivate students to be excellent • SLC organizes department golf tournaments and provides scholarships • Mentoring / Tutoring; pull TAs from SLC • Get students active and working together with their peers • Make students know that they are connected to other programs in other universities
Obstacles to having SLC	• Lack of understanding of what SLC is within the institution and industry • No active members currently • Faculty advisor's availability and commitment • Difficult to get a list of qualifying students • Students' lack of interest in organizations after COVID-19 pandemic • Have it recognized as an official student organization and receive funding from the university • Student involvement is low • Given the strong job market, an academic distinction is not a requirement for successful job placement.
Motivations for being an SLC advisor	• Enjoy recognizing students for their achievements. • Inducted when being a student • Know the value of SLC • Help students • Get students involved in non-academic activities and services
Support from SLC International	• Provide statistics or case studies on SLC members who have proceeded to the highest levels of success in CM • Provide additional assistance with recruiting and invitations • Connect Chapters with industry leaders looking for SLC members • Provide more networking opportunities, for example, the RENO event.
Support from department leaders	• Full support, encouragement, and budget • Commit to getting the SLC advisor a list of qualifying students within the first 4 weeks of each fall and spring semester

Most of the respondents state that SLC International has done a great job in supporting their chapters and they are satisfied with the support from their department leaders. Some of them give constructive suggestions which are listed in Table 2. This is a starting point and opens a conversation as to how SLC International and department leaders can support SLC faculty advisors better.

It is fortunate that this study has received timely responses from many SLC advisors and with 22 complete responses to the survey, statistical analysis is possible and is applied to the data set to further exploration of correlations. The first analysis is applied to the chapter induction ceremony numbers and inductee numbers for each chapter before and after the COVID-19 pandemic. The differences are calculated for each chapter and one-sample t-tests are performed to see if the differences are statistically significant. The result shows that there is moderate evidence that the number of induction ceremonies is reduced by an average of 0.5 times (p-value = 0.038) and the reduction in the number of inductees is not statistically significant (p-value = 0.135).

Another analysis is applied to see if SLC advisors' perspectives are related to their demographic differences. Survey scores for Part III questions are dependent variables and advisors' age, gender, academic position, years at current institution, and years being an SLC advisor are independent variables. Models are fit for each dependent variable with all independent variables. The p-values for all models are summarized in Table 3.

Table 3

P-values for ANOVA analysis

	Grade	Job placement	Service	Future leader	Communication	Campus leader
Age	0.203	0.436	0.351	0.672	0.324	0.423
Gender	0.399	0.052	0.087	0.021	0.098	0.344
Academic position	0.841	0.779	0.690	0.735	0.873	0.992
Years at current institution	0.411	0.456	0.995	0.642	0.693	0.529
Years being an SLC advisor	0.189	0.090	0.666	0.243	0.340	0.271

In Table 3, most of the p-values are greater than 0.1, which means there are no correlations. The significant results are responses for job placement, service, future leaders, and communication for different gender groups. Since the gender group only has two values, two-sample t-tests are performed to see the differences in these groups. Table 4 summarizes the results.

Table 4

Two-sample t-test results for different gender groups.

	Job placement	Service	Future leaders	Communication
Mean for Male	6.154	6.308	6.692	5.462
Mean for Female	3.222	3.111	3.111	2.333
Mean Difference	2.932	3.197	3.581	3.129
P-value	0.036	0.049	0.024	0.034

Table 4 shows that the male advisors are more convinced that joining SLC helps students with job placement than female advisors (mean difference = 2.932, p-value = 0.036). Male advisors are also more positive than female advisors in that joining SLC motivates students to provide services to local communities (mean difference = 3.197, p-value = 0.036), to become future leaders (mean difference = 3.581, p-value = 0.024), and to communicate better (mean difference = 3.129, p-value = 0.034). It is worth mentioning that these results only show correlations and they don't indicate any causation relationships. The results can't be inferred to a larger population and they only show the correlations of the 22 complete survey responses in this study.

Conclusions and Recommendations

A survey is developed to gather opinions from SLC faculty advisors to explore the benefits of joining SLC and the impact of the pandemic on SCL chapters. The survey was sent to 74 SLC faculty advisors and 22 complete responses were collected and used in this study. Results of the survey show that SLC members are more likely to be leaders on campus, but there is no apparent association between being a member of SLC and students' academic performance, job placement, service commitment, being future leaders, and better communication skills. The analysis shows that male advisors' responses are more positive than female advisors' responses regarding the benefits of joining SLC for students. However, these results only show correlations, and they don't indicate any causation relationships, and the conclusion can't be inferred to a larger population.

The analysis also shows that there is moderate evidence that the number of induction ceremonies for each SLC chapter is reduced by an average of 0.5 times after the COVID-19 pandemic and the reduction in the number of inductees due to COVID-19 is not statistically significant. In another word, this study shows that COVID-19 has very little impact on the number of inductees even though it greatly impacted how student clubs and honor societies operate during the pandemic. However, this study doesn't show the full picture of the pandemic's impact due to the nature of the voluntary surveying method. The advisors who responded to this survey could be very active advisors which can compensate for the negative impact of the pandemic.

The advisors believe that having an SLC chapter at their institution can motivate students to be excellent and be more active in working together with their peers. Another benefit of having an SLC chapter is to provide more networking opportunities for members to connect with alumni, industry professionals, and other students. The advisors identified a few obstacles to having an SLC chapter, including a lack of understanding of the value of SLC, faculty advisor's availability and commitment, students' lack of interest in organizations after the COVID-19 pandemic, and the difficulty to get a list of qualified students. The most common motivation for advisors to serve in this role is to help students. Most of the SLC faculty advisors feel that they have received adequate support from the SLC International office and their department leaders. Some of them suggest that the SLC International office can provide more opportunities for chapters to connect with industry leaders and other networking opportunities.

This study serves as the first step to exploring the benefits and issues related to joining the SLC Construction Honor Society. The results of this study come from SLC faculty advisors' opinions. To get a full picture, more students to explore similar issues from different angles are needed. For example, a survey to department heads may be used to further explore the enablers and inhibitors of having an SLC chapter in their institution. Another study could be developed to gather students' opinions on joining SLC. Getting employers' perspectives on hiring SLC members is also worth studying.

References

ACHS - Association of College Honor Societies (2022). http://www.achsnatl.org. Last accessed on Dec. 21, 2022.

Ferrari, J. R. et al. (2006). “Education and employment among alumni academic honor society leaders.” Education, Winter 2006, Vol. 127, No. 2, p244-259,

Gauer, J. L., & Jackson, J. B. (2017). “Association between the Medical College Admission Test scores and Alpha Omega Alpha Medical Honors Society membership.” Advances in Medical Education and Practice, 2017; 8: 627-632.

Hill, K. A. et al. (2022). “Association of marginalized identities with Alpha Omega Alpha Honor Society and Gold Humanism Honor Society membership among medical students.” JAMA Network Open, 2022, Vol. 5, No. 9.

Hopkins, E. E. et al. (2015). “Creating a virtual nursing honor society: key technology design considerations.” Journal of Nursing Education and Practice, Vol. 5, No. 2, p131-135.

Hopkins, E. E. et al. (2016). “Honor society membership retention strategies: promoting membership benefits from induction through transition to professional practice.” Journal of Nursing Education and Practice, Vol. 6, No. 12, p18-23.

Rosenthal, S. et al (2009). “Does medical student membership in the Gold Humanism Honor Society influence selection for residency?” Journal of Surgical Education, November/December 2009, Vol. 66, No. 6, p308-313.

SLC - Sigma Lambda Chi International Construction Honor Society (2022). “About the society”. https://www.slc-intl.org/about-the-society. Last accessed on Dec.21, 2022.

Specter, S. et al (2015). “Gold Humanism Honor Society election and academic outcomes: a 10-institution study.” Family Medicine, November/December 2015, Vol. 47, No. 10, p770-775.

Watkins, S. E., & Ostin, N. M. (2018). “Best Practices of Honor Societies” ASEE Gulf-Southwest Section Annual Meeting, AT&T Executive Education and Conference Center, Austin, TX 78705.

A Gamified Pedagogical Method for Teaching Construction Scheduling through Active Exploration

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Previous studies have convincingly shown that active and collaborative instructions, coupled with effective means to encourage student engagement, invariably lead to better learning outcomes. However, despite significant potentials for experiential learning, standard educational programs in construction engineering and management are rigid systems that offer little opportunity for students to engage in active learning that can help them gain first-hand experience and guide them toward discovering solutions. This study aims to address this need by designing and empirically assessing the performance of a novel gamified pedagogical method that teaches construction scheduling through guided active exploration in a digital game environment. The proposed pedagogical approach and its game are designed based on the constructivism learning theory. A scenario-based interactive game, called *Zebel*, was developed using the Unity game engine. Using a series of pre- and post-assessment instruments, the proposed method was implemented and evaluated in a graduate-level course for construction planning and scheduling to collect empirical data. The outcomes indicated that the proposed pedagogy was able to successfully guide students with no background and prior knowledge in construction scheduling to discover the fundamental concepts and systematic solutions for the problems.

Key Words: Gamified Pedagogy, Active Exploration, Construction Scheduling, Constructivism

Introduction

The history of construction dates back to the Neolithic era (i.e., New Stone Age), roughly from 9000 BC to 5000 BC (Violatti 2018). Many prehistoric structures, including megalithic temples in Malta (from around 3600 BC) and the Egyptian pyramids (from around 2500 BC) are still standing. However, Newton's laws of motion, which laid the foundation for classical mechanics and, consequently, structural analysis, were first published in 1687, only 336 years ago. For thousands of years, structures were built without formal theories that mathematically explain why they stand. The evolution of construction engineering from ancient times to the seventeenth century was mainly based on discoveries through trial and error that helped craftsmen empirically distinguish good design and construction methods from less effective approaches (Abrams 1994). From the seventeenth century, when Newton presented his laws of motion, engineering concepts gradually developed stronger connections with mathematical expressions. The mathematical representation of engineering concepts is the foundation of modern engineering and engineering education. There is no doubt about the necessity of mathematical expression for engineering topics. However, through time, educational programs in many engineering fields, including construction, have evolved into rigid systems that mainly train students to follow specific procedural algorithms for inserting data into well-defined equations and calculating expected outcomes for closed-ended problems. These educational programs offer little opportunity for students to engage in active learning that can help them gain first-hand experience and guide them toward discovering solutions. However, previous studies have convincingly shown that active and collaborative instructions, coupled with effective means to encourage student engagement, invariably lead to better student learning outcomes (Kuh et al. 2011, Weimer 2022). Therefore, recently, designing learning methods based on active exploration has received attention in various fields including construction. The long history of empirical learning in the field of construction engineering shows the significant potential of cognitive development through direct experience and reflection on what works in particular situations (Boothby 2018). Of course, the complex nature of the construction industry in the twenty-first century cannot afford an education through trial and error in the real environment. However, recent advances in computer science can help educators develop virtual environments and game platforms that allow students to explore various scenarios and learn from their experiences. Ilbeigi et al. (2023) conducted a systematic review of more than one hundred studies focused on gamification for construction engineering education. Although they observed a clear upward trend in the number of studies proposing gamified solutions for education and training, they listed a set of potential directions for future studies. One of the potential topics is to use games as facilitator for learning through active exploration. The overarching objective of this study is to design and empirically assess the performance of a novel gamified pedagogical method that teaches construction scheduling through guided active exploration in a digital game environment. More specifically, we examine whether guided active exploration in a digital game environment improves students' ability to discover systematic strategies to solve fundamental problems in construction scheduling. To address this objective, the remainder of this paper is organized as follows. After a brief introduction to gamification in education, we present the methodology, including the design of the gamified approach and assessment strategy. Next, we describe the implementation outcomes. Finally, we summarize the results, discuss the contributions of this study to the body of knowledge, and depict future research directions.

Gamification

Gamification or serious games apply game elements and principles in non-game contexts (Dicheva et al., 2015). If appropriately designed, serious games can provide an interactive environment where users can engage with technical contexts, explore different scenarios, acquire new knowledge, and connect that knowledge to their existing mental models (Deshpande and Huang 2011). The term gamification was coined by Nick Pelling in 2002 and hit the mainstream around 2010 (Pelling 2011). The elements of a gamified system can be categorized into three groups: (1) Dynamics: which defines the big picture aspect of the game and includes elements such as constraints, narratives, progression, and relationships, (2) Mechanics: which defines the processes that drive actions forward and includes elements such as challenges, chance, competition, cooperation, feedback, resource acquisition, rewards, transactions, turns, and win states, and (3) Components: that shows specific instantiations of mechanics and dynamics and includes elements such as points, quests, achievements, badges, avatars, and virtual goods (Werbach and Hunter 2012).

Methodology

The envisioned methodology in this study revolves around two components: (1) the game and (2) the assessment strategy to evaluate the effectiveness of the proposed gamified pedagogy. In this section, first, we introduce the game and its characteristics. Next, we present the assessment instruments and empirical data collection strategy.

Zebel: An Interactive Game for Construction Scheduling

To address the objective of this study, we designed and developed an online game called *Zebel*. The game is a mobile/tablet application that provides an interactive digital environment in which users try to solve fundamental problems in the domain of construction planning and scheduling presented in realistic scenarios through guided active explorations. Figure 1 shows a snapshot of the game. The scenario-based problems facilitate sense-making and engage students in understanding, analyzing, and solving open-ended problems in that field. During the active explorations to solve these fundamental problems, the users are exposed to fundamental engineering problems and try to discover systematic solutions to solve them. The game and the proposed gamified pedagogy are designed based on the Constructivism learning theory.

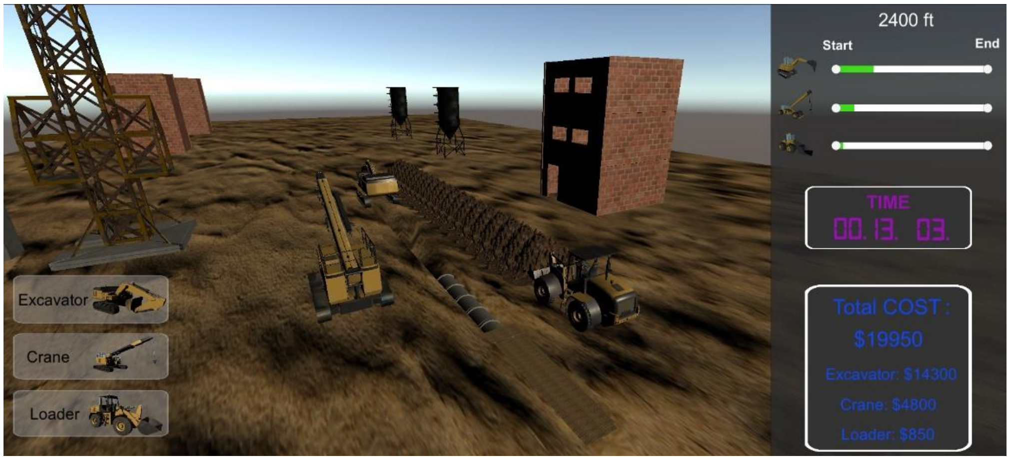

Figure 1: A snapshot of the Zebel game

Constructivism Theoretical Framework

Constructivism learning theory was created based on the theory of cognitive development by Piaget (1952). A long list of researchers including Bruner (1966), Ausubel and Robinson (1969), and Maturana (2006) contributed to this theory and made it the most prevalent variant of cognitivism (Tobias 2010). This learning theory assumes that knowledge is constructed by learners as they attempt to make sense of their observations (Driscoll 2000). The focus of constructivism is on knowledge construction rather than knowledge transmission (Sheppard et al. 2009). The principle of constructivism is an individualized representation of knowledge based on active exploration and learning by interaction, in which learners build on their own individual experiences when they uncover an inconsistency between their current knowledge representation and their new experience (Tobias 2010). The constructivist view of learning has been embraced by the gamification world (Driscoll 2000). The proposed gamified approach in this project is guided by a constructivist framework developed specifically for learning through gamification (Newstetter and Svinicki 2015). This learning framework is based on the following six essentials (Figure 2):

1. **Modeling**: This involves taking advantage of the learners' prior knowledge and providing them with background knowledge related to the learning objectives of the game. The goal of modeling is to enable students to build a conceptual model of the process required to attain the game's learning objectives.
2. **Reflection**: This involves the process by which the learners logically organize their thoughts and connect their preliminary ideas to separate the more important presumptions from less important ones. The modeling and the reflection phases help learners form their personal synthesis of knowledge that initiates the process of strategy formation.
3. **Strategy Formation**: This involves the learners' efforts to form appropriate playing strategies to solve the problems the game provides.
4. **Scaffolded Exploration**: This involves the learners' exploration of the scaffolded game world, where they perceive the impacts and consequences of their actions through various game elements. The aim is to guide the learners to a mode of problem-solving on their own through the support that the game provides as they carry out different activities.
5. **Debriefing**: This involves a description of events that occurred in the game, an analysis of why they occurred, and the discussion of mistakes and corrective actions by learners. Debriefing is a fundamental link between game experiences and learning that helps learners deconstruct the activity and then connect it to their mental models.
6. **Articulation**: This involves students' sharing of their game experience and acquired knowledge to progress toward collective goals of understanding. Articulation encourages the social negotiation of meaning that is a primary means of solving problems, building personal knowledge, establishing an identity, and most other functions performed in teams.

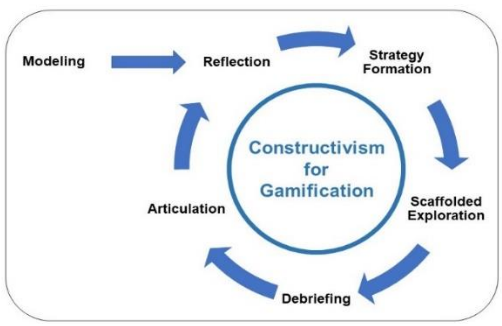

Figure 2: Constructivism framework for gamification

The game has been designed based on these six essentials. Regarding the Modeling process, students who will use the game have some levels of understanding about construction projects. The game also uses animated demonstration videos to provide background information about the construction scenarios. For example, in each chapter of the game, a short animation introduces the problem, objectives, tasks, and resources, including different types of heavy equipment involved in that scenario-based problem. For the Reflection, students' prior knowledge and the design of the game and its features will give students ideas about the objectives of the game, how to start it, and how to proceed. For Strategy Formation, after understanding the game and its features, students will start thinking about how to use available resources to solve the problem. For example, what type and how many pieces of each type of equipment are needed to successfully solve the problem, considering limitations such as available budget and time? Regarding the Scaffolded Exploration, in the game, students are able to perceive the consequences of their actions constantly through game elements such as points and resource utilization. Depending on the complexity of a problem and the student's performance, the game may provide them with some hints as well. Eventually, based on the students' progress, feedback from the game, and new information that is added to the student's cognitive organization, the students can adjust their actions and update their strategies. For Debriefing, depending on the scenario of the game and students' performance, Zebel sometimes prompts users to explain their observations, outcomes of their decisions, and strategies to solve the problem. Students will be asked to type their responses in a pop-up box. Finally, for the Articulation step, the game platform provides an online forum where students interface with their peers and share their ideas and findings. The forum also allows students to ask questions and discuss each other's comments and ideas.

Design of the Game

The first chapter of the game, which is the focus of this study, concentrates on the Critical Path Method (CPM) for learners with no prior knowledge and experience in scheduling. CPM is the most common method of scheduling in construction projects. It determines the order of activities and their start and finish times based on their logical dependencies and timing flexibility due to parallel paths through the network of activities. The timing flexibility in an activity, also known as float or slack, is an essential concept in understanding how the CPM works and prioritizes activities in response to limited resources. The first chapter of the game aims to direct students to discover this concept and its application in scheduling a construction project with limited resources through active exploration.

This part of the game provides the students with a scenario in which they need to schedule a set of heavy construction activities in two adjacent sites, i.e., East and West sites. Figure 3 shows the demo of the game. Figure 4 shows a snapshot of the gameplay. The East side has more activities with longer durations compared to the West side. The activities on both sides share a limited number of heavy equipment (e.g., dozer, grader). In some cases, the user needs to determine which activity should have priority to get the equipment and which ones should be postponed while finishing the entire project (i.e., both East and West side) in the shortest possible time. This scenario aims to guide the students to discover three fundamental facts: 1) not all activities have the same level of criticality in terms of being done as soon as possible, 2) critical activities form the longest path in the network of activities, 3) non-critical activities can be delayed to some extent without affecting the completion time of the project, and 4) delaying non-critical activities can be a solution to address the issue of limited resources in a project.

Figure 3: Demo of the game

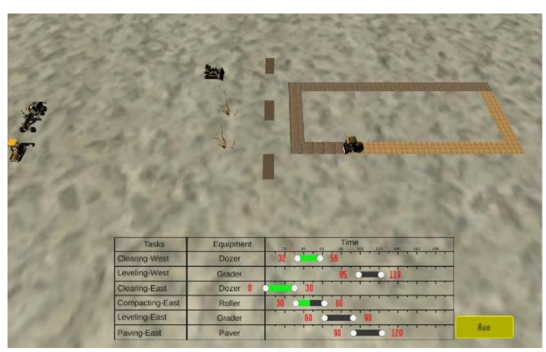

Figure 4: Snapshot of the game play

While playing, after learning about the tasks, equipment, and constraints of the game through a demo, the students will plan a preliminary strategy and guess a start time for each activity, observe the outcomes of their decisions, receive feedback from the game, adjust their strategy, and keep trying until they achieve the goal. They are also required to explain their observations and strategies through the game's debriefing mechanism. Particularly, when a user achieves the goal, the debriefing mechanism will ask the user to come up with a systematic approach to solve this type of problem (Figure 5). After recording the response, the game shows a diagram highlighting the floats in each non-critical activity in the game without any explicit explanation (Figure 6) and repeats the question to check whether the users change their proposed strategy after seeing the diagram.

The Zebel game was created using the Unity game development platform. Unity is a cloud-based game development engine that provides a wide range of services, including a software development kit (SDK), an application programming interface (API), a series of game object libraries, plugins, and predefined functionalities. For the game's debriefing and articulation mechanisms, a cloud-based application was developed to collect user and usage information using a RESTful web service utilizing node JS on Firebase, a Google cloud solution platform. Upon completion of each game, either successfully or by running out of time, the user's activity log and other relevant information will be decoded into a JSON document and submitted to the backend over the Internet. This data, along with user information, is saved into a NoSQL database to be post-processed.

After the successful completion of the first scenario and recording students' inputs, the game provides two relatively more complicated scenarios to expose the students to different consequences of delaying critical activities versus non-critical ones. Finally, the game will ask students to determine critical activities in this project. Right after finishing the game, students have access to the online articulation platform to share their experiences and discuss their strategies together.

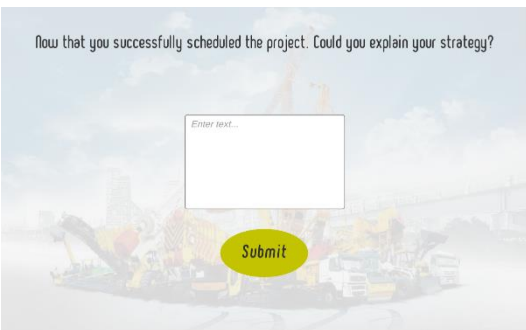

Figure 5: Debriefing mechanism

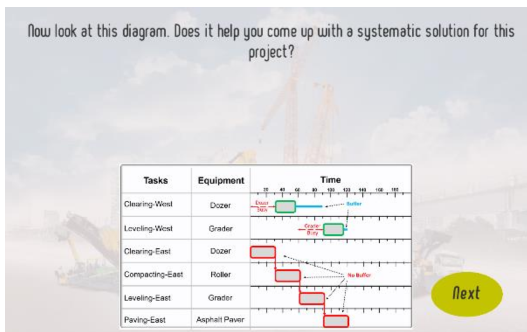

Figure 6: Providing hints

Assessment Instruments

The effectiveness of the proposed gamified pedagogical approach is assessed through four instruments: 1) a prior knowledge survey, 2) a benchmark exam, 3) a game assignment, and 4) a post-game exam. The prior knowledge survey, administered in the first session of the class, aims to identify students who have had exposure to standard ways to solve these problems. If some students have considerable prior knowledge of the target topics, their data are excluded from the assessment analyses. The benchmark exam, conducted in the first session of the class, aims to evaluate students' understanding of the fundamental concepts in scheduling, such as float. The game assignment requires students to use and successfully finish the Zebel game. The game platform records all students' inputs and decisions in log files. Analyzing the log files shows how students set their strategies and update them throughout the game. Finally, the post-game exam, administered a week after the game assignment, is designed to align with the benchmark exam to evaluate students' progress in the understanding of the fundamental concepts after their experience with the game.

Empirical Data Collection

The proposed gamified pedagogical method was implemented in a graduate-level course titled *CM-529: Construction Planning and Scheduling* in the Department of Civil, Environmental, and Ocean Engineering (CEOE) at Stevens Institute of Technology in Fall 2022. The Zebel game served as a formal teaching tool. Forty students registered for the course during that semester. As this project seeks to understand personal information about human subjects, including students' individual perceptions, Institutional Review Board (IRB) requirements and approval were secured before conducting the study. Consent forms were administered on the first day of class, and the students were informed that some of the classroom activities and assignments would be monitored as part of a research project. Students had the opportunity to opt-out, with no impact on their grades, in which case their assignments would be excluded from the research findings. All 40 students agreed to participate in this study. The results of the prior knowledge survey indicated that 10 students had some level of familiarity with the fundamentals of CPM. Their game data was excluded from the analysis process in this study. The students worked on the game assignment in the second week of the class before any introduction to CPM and its fundamental concepts, including float and using it to address resource allocation problems in parallel chains of activities.

Analysis and Results

The recorded data indicated that 27 out of the 30 students with no prior knowledge of CPM worked on the assignment and submitted it before the deadline. The average number of trials to accomplish the game was 4.51, with a minimum of 1 and a maximum of 17 tries. The recorded log files indicate that students tend to schedule everything as soon as possible and gradually learn that they have to delay some of them to manage their resources. Although the demo of the game aimed to explain the scenario of the project, a considerable number of students made some mistakes in setting the activities in a logical order (e.g., clearing the site by a dozer should proceed with leveling the site by a grader) in their early trials. More specifically, 36% of the generated error messages to guide students to fix their strategies were related to the order of the activities. In total, 21 students received this message, but all of them were able to fix the issue in the following rounds. In addition, 13% of the error messages were related to overlapping activities on one side of the project. As noted before, the demonstration of the scenario asks students not to overlap activities on one side of the project for the sake of simplicity. However, they can overlap activities from one side of the project to those on the other side. Like the error related to the logical order of the activities, this error message mostly happened in the early rounds of students' trials.

Regarding the limited resource issue, 27% of the error messages reminded students that they have only one piece of equipment for each type, but their current schedule needs at least one type of equipment on both sides at the same time. Finding a solution to address this issue is the main learning objective of the proposed gamified pedagogy. All students were able to find the solution and solve this problem by postponing the non-critical activities on the west side of the project. Finally, 24% of the generated error messages informed the students that their schedule was correct in terms of the order of the activities and addressing the resource allocation problem; however, the total duration of the project could be shorter.

The students' inputs in the debriefing mechanism of the game asking them to describe their strategy indicate that throughout the game, they gradually noticed that not all activities in a project necessarily have the same level of time sensitivity and they could be postponed intentionally to address the resource allocation problem and assign the limited resources to the activities that are more critical to be done as soon as possible for minimizing the total duration of the project. The results also indicate that students understood that the flexibility (i.e., float) in the start time of a non-critical activity is limited, and they may become critical after a certain amount of delay. Finally, the strategies described by the students showed that they were able to understand that the floats (i.e., flexibility in the timing of some activities) are created because of the parallel chains of activities. In the last part of the game, students were asked to list the critical activities in the project, and more than half of them (i.e., 15 out of 27) were able to completely identify the critical activities in the project. Immediately upon completing the game assignment, students had access to the articulation platform to share their experiences and discuss their strategies. In total, 30 comments were submitted by the students, and they engaged in discussions. All comments were positive.

In the following session after the game assignment, the post-game exam was administered. The questions in the post-game exam were aligned with the questions in the benchmark exam. All the 27 students who did not show any indication of familiarity with CPM and its fundamental concepts, such as float, were able to answer the post-game questions correctly. "*Doing an assignment by playing a game is the most unique and interactive way of learning the subject content I have ever done*," one of the students noted on the platform. "*This way of teaching does stay in the mind for a longer period of time than regular teaching*" another student commented. "*Although this evaluation is presented in the form of a simple interactive game, it still presents and demonstrates the real-world problems one will encounter as a project manager/construction manager in the field*" one of the students with professional experience in construction scheduling noted. In addition, many students engaged in detailed discussions about their strategies and how they realized the correct solution.

Conclusion

In this study, a novel gamified pedagogical method was designed, and its effectiveness on students' ability to discover systematic solutions for fundamental construction scheduling problems was empirically assessed. The proposed pedagogical method and its game were developed based on the constructivism learning theory. The empirical data collected through pre- and post-assessment instruments, in addition to recorded log files, indicate that the proposed gamified method was able to introduce the students to fundamental concepts in CPM, including overlapping activities, critical activities, floats, and their application for resource management through active exploration in an interactive digital game environment. All students were able to successfully finish the game and accomplish its goal. The recorded data in the debriefing mechanism of the game showed clear evidence indicating that all students realized that some activities are less time sensitive and can be postponed in response to resource allocation problems. In the end, more than half of the students who never had any exposure to CPM and its fundamental concepts were able to correctly list the critical activities. The data collected through the articulation platform indicated that students perceived the proposed gamified pedagogy as interesting, engaging, and effective. The outcomes of the pre- and post-assessments (i.e., a post-game exam compared to a benchmark exam) indicated that the proposed method was able to help all students define and identify critical activities and effectively use floats to address resource allocation problems. This study is part of an ongoing research project. More data will be collected from the students via surveys and semi-structured interviews to analyze their experiences throughout the proposed learning method more rigorously and better understand the strengths and limitations of the proposed pedagogy. These will be the foundations for future studies.

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References

Abrams, E. M. (1994). How the Maya built their world: energetics and ancient architecture. University of Texas Press.

Ausubel, D. P., & Robinson, F. G. (1969). School learning: An introduction to educational psychology. Holt, Rinehart Winston. New York.

Boothby, T. (2018). Empirical Structural Design for Architects, Engineers and Builders. Institute of Civil Engineers (ICE) Publishing. London. United Kingdom.

Bruner, J. S. (1966). Toward a theory of instruction (Vol. 59). Harvard University Press.

Deshpande, A. A., & Huang, S. H. (2011). Simulation games in engineering education: A state-of-the-art review. *Computer applications in engineering education*, *19*(3), 399-410.

Dicheva, D., Dichev, C., Agre, G., & Angelova, G. (2015). Gamification in education: A systematic mapping study. *Journal of Educational Technology & Society*, *18*(3).

Driscoll, M. P. (2000). Psychology of learning for instruction, 2nd ed. Needham Heights, MA: Allyn and Bacon.

Ilbeigi, M., Bairaktarova, D., & Morteza, A. (2023). Gamification in Construction Engineering Education: A Scoping Review. *Journal of Civil Engineering Education*, 149(2), 04022012.

Kuh, G. D., Kinzie, J., Schuh, J. H., & Whitt, E. J. (2011). Student success in college: Creating conditions that matter. John Wiley & Sons.

Maturana, H. R. (2006). Self-consciousness: how? when? where?. *Constructivist Foundations*, 1(3).

Newstetter, W. C., & Svinicki, M. D. (2015). Learning theories for engineering education practice. In *Cambridge handbook of engineering education research* (pp. 29-46). Cambridge University Press.

Pelling, N. (2011). The (short) prehistory of gamification. *Funding Startups (& other impossibilities)*, 9.

Piaget, J. (1952). The origins of intelligence in children. W W Norton & Co. New York.

Sheppard, S., Macatangay, K., Colby, A., Sullivan, W. M., & Shulman, L. S. (2009). *Educating engineers: Designing for the future of the field* (Vol. 9). San Francisco, CA: Jossey-Bass.

Tobias, S. (2010). Generative learning theory, paradigm shifts, and constructivism in educational psychology: A tribute to Merl Wittrock. *Educational Psychologist*, *45*(1), 51-54.

Violatti, C. (2018). Neolithic Period. *Ancient History*. Retrieved from https://www.ancient.eu/Neolithic/

Weimer, M. (2002). Learner-centered teaching: Five key changes to practice. John Wiley & Sons.

Werbach, K., & Hunter, D. (2013). For the Win: How Game Thinking Can Revolutionize Your Business. Wharton Digital Press. Philadelphia, PA.

Best Management Practices for Grease Interceptors and Sanitary Sewer System Protection in Nashville, TN

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Worldwide, approximately 40-50% of annual Sanitary Sewer Systems blockages are caused by fat, oil, and grease. This research study reviewed the issue of fat, oil and grease produced by Food Service Establishments and the impact this has on Sanitary Sewer Systems and measures available as prevention. Additionally, this research focused on the EPA Code of Regulations and the Nashville, TN Code of Ordinances, that determine types of grease control systems, required maintenance, along with Food Service Establishments compliance, and implementation of Best Management Practices (BMPs). A survey of twenty (20) Food Service Establishments in Nashville, TN was conducted to understand the necessity for Grease Interceptors and other preventative measures such as self-managed Food Service Operation BMPs and their ability to prevent and protect the Sanitary Sewer System. The survey analysis details that Food Service Operations BMPs are sporadic at best and further research is needed in this area of Sanitary Sewer System protection.

Keywords: BMPs, Grease Interceptors, Sanitary Sewer, Food Service Operations

Introduction

Fat, Oil and Grease (FOG) in sewer systems are primarily discharged from Food Service Establishments (FSEs) [...] FOG deposits are responsible for approximately 40-50% of the annual blockage related to sanitary sewer overflows (SSOs) (He et al., 2017).

Sanitary sewer overflows (SSOs) are the discharge of untreated sewage to the environment prior to reaching the wastewater treatment plant. These unlawful discharges may spread high concentrations of pathogens, nutrients, and solids, resulting in a series of environmental problems that threaten human and environmental health. Approximately 23,000-75,000 SSO events are reported annually by the US EPA and release 3-10 billion gallons of untreated wastewater to the environment. Half of those SSOs are attributed to partial or full pipe blockages, which are triggered by the accumulation of insoluble fat, oil, and grease (FOG) deposits (Hao et al., 2017).

In order to protect SSOs, cities, and states derive their authority and establishes the basic structure for regulating discharges of pollutants into the waters from the Environmental Protection Agency, Code of Federal Regulations, Title, Part 403.5, National Pretreatment standards: Prohibited discharges (a)(1) General prohibitions. A User may not introduce into a POTW (Publicly Owned Treatment Works) any pollutant(s) which cause Pass Through or Interference. (B)(3) Solid or viscous pollutants in amounts which will obstruct the flow in the (POTW) resulting in Interference; (4) POTWs may develop Best Management Practices to Implement ((c)(1) and ((c)(2)…[wherein] each POTW with an approved pretreatment program shall continue to develop these limits and effectively enforce such limits (40 CFR 403.5 - National Pretreatment Standards, n.d.).

Metro Government of Nashville and Davison County, TN Code of Ordinances Chapter 15.04.310 defines, 'Pretreatment' as the reduction of the amount of pollutants, the elimination of pollutants, or the alteration of the nature of pollutant properties in wastewater to a less harmful state prior to or in lieu of discharging or otherwise introducing such pollutants into a POTW. The reduction or alteration can be obtained by physical, chemical, or biological processes, process changes, or by other means, except as prohibited by 40 CFR Section 403.6(d). Additionally, Chapter 15.60, Industrial Waste Discharge, section 15.60.125 states, all food service establishments are required to comply with Operation Division Policy No. 2004-01: Metro Water Services Fats, Oils and Grease Management Policy (Mini TOC: Title 15 - WATER, SEWERS AND OTHER PUBLIC SERVICES | Code of Ordinances | Metro Government of Nashville and Davidson County, TN | Municode Library, n.d.).

Research Objective

The objective of this research is to identify the problem with FOG, the systems available to prevent build-up, and subsequent blockage of the local sanitary sewer system, and FSEs BMPs to prevent FOG from entering the SSO. Research primarily focused on the Nashville, TN, Metro Water Service, Fats, Oil, and Grease Management Policy, and a survey of Nashville FSEs; however, it did take a broader look at national standards for reference. The data compiled will be used to determine the self-management of BMPs and the following of grease interceptor servicing and cleaning requirements.

Background

What is FOG

FOG is a mixture of fats, lipids, and oil generated from wastewater of Food Service Establishments (FSE) such as restaurants, bakeries, and coffee shops (Hao et al., 2017).

Wastewater from restaurants typically contains large amounts of organic matter (biochemical oxygen demand, BOD), greases, and oils. The term oil and grease, as commonly used, includes fats, oils, waxes, and other related constituents found in wastewater. These are compounds (esters) of alcohol or glycerol with fatty acids. The glycerides of fatty acids that are liquid at ordinary temperatures are called oils, and those that are solids are called grease (or fats). In the absence of industrial products, oil and grease is composed primarily of fatty matter from animal and vegetable sources and hydrocarbons of petroleum origin. […] Oils and greases may influence wastewater treatment systems if present in excessive amounts. They may interfere with aerobic and anaerobic biological processes and lead to decreased wastewater treatment efficiency. When discharged in wastewater or treated effluents, they may cause surface films and shoreline deposits, leading to environmental degradation. […] Greases and oils are persistent for extended periods and could be troublesome. The concentration of oil and grease in wastewater from restaurants could vary from about 1000 mg/I to more than 2000 mg/I. The effluent oil and grease concentration should be less than about 30 mg/1 to avoid problems with downstream treatment units in decentralized wastewater treatment and disposal systems such as OSSF systems (LitReviewOnTheEval.pdf, n.d.).

Why is FOG a Problem

Food Service Establishment's (FSE) drains and sewers often suffer from blockages caused by the accumulation of fat, oil, and grease (FOG), resulting in backup and flooding of wastewater on-site and within the local environment. These problems are generally caused by inadequate on-site pretreatment of the wastewater and, more importantly, by failure to take wastewater characteristics into account when designing the system (e.g., grease interceptors GI, grease removal units GRU, or biological additions)(Gurd et al., 2019).

It was initially hypothesized that FOG from FSE discharges interacts with calcium from wastewater, leading to the formation of the calcium-based fatty acid salts or FOG deposits through a saponification reaction. This hypothesis was later verified by the formation of FOG deposits under laboratory conditions from the reaction between free fatty acids (FFAs) and calcium chloride. These lab-based FOG deposits were shown to have a strong similarity to FOG deposits collected from sewer lines and pure calcium soaps using Fourier Transform Infrared (FTIR) analysis, which provided evidence that hardened FOG deposits were indeed born from saponification. The adhesive quality of the saponified solid material may be attributed to the composition of FFAs and the ratio of FOG/calcium involved in the saponification reaction (He et al., 2017).

FFAs are primarily generated from the hydrolysis of FOG. During the cooking process (e.g., deep fat frying, baking, and grilling), fast hydrolysis has been found to generate FFAs as soon as the fat comes in contact with moisture. Researchers have also suggested that FFAs may be produced through alkali driven hydrolysis in GIs near the inlet, along the sewer line due to prolonged contact or mixing between FOG and high moisture, and at sewer crowns due to the release of calcium hydroxide from concrete corrosion (He et al., 2017).

The debris layer found in sewer-based FOG deposits is suspected to result from the cleaning and sanitizing of nonfood-contact surfaces in the facility. Dirt and debris from floors, tables, and walls may be rinsed into sanitary sewers and accumulates at the FOG deposit site. Grit and rust from a wide variety of unknown sources that end up in sewers have also been found in FOG deposits. Although peptide and or proteins were detected in FOG deposits, no study has been performed to determine the original source of these compounds. Furthermore, the adsorption of hydrophobic substances between FOG and flushable consumer products (FCPs), such as toilet tissue and wet wipes, may also lead to the accumulation of FCPs as debris in FOG deposits. While there is no way to know how much debris will accumulate on the surface or internally within the FOG deposit core matrix, the tackiness and rheology of the typical FOG deposit will continue to attract and retain debris found in the typical sewer collection system and exacerbate the pipe blockage (He et al., 2017).

Grease Interceptors

Ideally, FOG would never go down the drain. However, at this time, most restaurants cannot keep 100% of FOG out of the collection system. This is why FOG removal devices and proper maintenance of these devices are so important (Tennessee Guidance Doc.pdf, n.d.).

Grease interceptors, either below the sink (flow-based grease interceptors or FGI) or outside and below ground (retention-based grease interceptors or RGI), are the primary approaches for removing FOG from FSE effluent. Both FGIs and RGIs work under the principles of gravity separation, which allows for the accumulation of FOG at the surface and the settling of food solids and kitchen debris at the bottom. The clarified water is then discharged to the sanitary sewer system. Depending on the size of food processing operations, the installation of GIs for FSEs (e.g., restaurants and hotels) is globally required by numerous municipalities (He et al., 2017).

The tank (Figure 1) shall be of a monolithic body design, separated by a solid baffle into 2/3 total capacity inlet chamber and 1/3 total capacity outlet chamber. It shall have 24" access ways over each drop tee. Flow-through the baffles will be provided by a 90-degree sweep. All perforations and seems shall be sealed with hydraulic cement or welded. All piping shall be a minimum of schedule 40 PVC solvent welded; pipe clamps or hangers may be required. All parts of the system shall be made water and gas-tight from two-way cleanout upstream of the tank to two-way cleanout downstream of the tank, including andy risers to grade; proper venting allowed (FOG Management Policy_effective 07.01.14_stamped by Metro Clerk.pdf, n.d.).

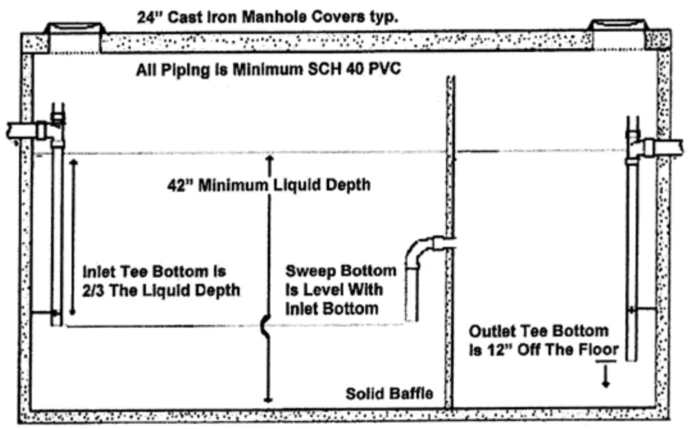

Figure 1: Grease Interceptor – Metro Water Services

How Grease Interceptors work

A grease trap or interceptor consists of an enclosed chamber, which is designed to separate and retain oil and grease from the kitchen wastewater. Separation is accomplished by virtue of the fact that fats and grease have a lower specific gravity (are less dense) than water and rise to the surface under favorable conditions. Treated wastewater passes through the chamber and on to the sewer. In order to ensure efficient operation, the separation device must be cleaned periodically to remove the accumulated grease and settled solids and to restore the required separation volume allowed (Tennessee Guidance Doc.pdf, n.d.). Grease traps and interceptors must be designed to satisfy three basic criteria in order to ensure effective separation: these are time, temperature, and turbulence (Tennessee Guidance Doc.pdf, n.d.).

1) Time. The separation device must provide sufficient retention time for emulsified grease and oil to separate and float to the surface of the chamber.
2) Temperature. The separation device must provide adequate volume to allow the wastewater to cool sufficiently for emulsified grease to separate.
3) Turbulence. Turbulence through the device must be controlled so that grease and solids are not kept in suspension in the wastewater. Turbulence must be controlled, especially during high discharge rates associated with draining a triple sink or multiple fixtures simultaneously.

In addition, the grease trap or interceptor must provide sufficient storage capacity for accumulated grease (the floating particles) and solids (the settling particles) between cleanings allowed (Tennessee Guidance Doc.pdf, n.d.).

Grease Interceptor Cleaning and Maintenance Requirements

An obvious required cleaning interval of an interceptor is when it is full of FOG. Actually, however logical that statement first appears, it is false. When the interceptor is full, it is too late. It is too late to maintain water quality, and it is too late to prevent damage to the interceptor, the building's drainage piping, and the collection system. A rule of thumb, though not formally prescribed by code and rarely by pretreatment administrators, is 25 percent of the wetted area of the interceptor. That is, whenever accumulated material floating or at the interceptor bottom, whichever occurs first, or the two combined equal 25 percent of the vertical height of the wetted surface at static (non-flowing) conditions, the interceptor requires cleaning. […] All interceptors containing excessive FOG and aged FOG will demonstrate a dramatic reduction in separation and retention efficiency. In addition, the potential for interceptor and collection system obstruction increases exponentially with the duration of FOG retention (FACTS and MYTHS Grease Interceptor by Max Weiss, 2007).

The ultimate disposal of FOG is an essential part of a FOG control program. If grease trap pumpers do not do an adequate job of cleaning a grease interceptor/trap or if they discharge the contents of the grease trap into a manhole, the other aspects of the grease control program cannot be effective (Tennessee Guidance Doc.pdf, n.d.).

The following are the Nashville Metro Water Service, Grease Interceptor Cleaning and Maintenance Requirements (FOG Management Policy effective 07.01.14_stamped by Metro Clerk.pdf, n.d.):

1. Cleaning / Pumping - Grease interceptors must have the complete contents pumped or cleaned at a frequency of not less than once every 90 days unless approved in writing by the Department of Water Services. Also, grease interceptors must have a complete pump of contents when the total accumulations of surface FOG (including floating solids) and settled solids combined reaches twenty-five percent (25%) of the grease interceptor's overall liquid depth. This criterion is referred to as the "25 Percent Rule".
2. Partial pump of interceptor contents or on-site pump & treatment of interceptor contents will not be allowed due to the reintroduction of fats, oils, and grease to the interceptor and pursuant to the Code Federal Regulation (CFR) § 403.5 (b) (8), which states "Specific prohibitions. In addition, the following pollutants shall not be introduced into a POTW: Any trucked or hauled pollutants, except at discharge points designated by the POTW".
3. The Grease interceptor effluent-tee will be inspected during cleaning and maintenance and the condition noted by the grease waste hauler's company or individual conducting the maintenance. The hauler or individual conducting the maintenance will contact the FSE to make them aware of any defects identified. Effluent-tees that are loose, defective, or not attached must be repaired or replaced immediately.
4. Grease Interceptors must have access manholes over the influent-tee and effluent-tee for inspection and ease of cleaning/maintenance. Access manholes are required for all compartments for complete cleaning.
5. Grease Interceptors must be "certified" annually by a Metro Water Services approved grease waste hauler or plumber.

Best Management Practices (BMPs)

Preventing FOG build-up in the collection system is the goal of FOG control measures. Many cities have found that requiring restaurants to implement Best Management Practices (BMPs) is an effective tool in controlling FOG without requiring extensive monitoring. (Nashville > Water Services > Environmental Compliance, n.d.). Below is a consolidated list of 'typical' BMPs.

ID	Best Management Practices (BMPs)
•	***Food Service Operations BMPs***

1	Dry Wipe Pots, Pans & Dishware before washing
2	Training of Proper Grease Handling in Restaurant
3	Recycle Waste Cooking Oil
4	DO NOT pour Grease into Sinks or Floor Drains
5	'No Grease' Signs over Sinks & Drains
6	Strainers in Sinks to Prevent large Food Particles from Entering the Sewer System
7	Strainers in Floor Drains to Prevent large Food Particles from Entering the Sewer System
8	Grease & Oil Spill procedures to prevent entering the Drains
9	Ensure 'Food Grinder' is not attached to Sewer System
•	***Grease Interceptor BMPs***
10	Pump Out Grease Interceptors regularly
11	Clean Grease Interceptors regularly
12	Witness Grease Interceptor Pump Out/Cleaning
13	Retain Signed Copies of Grease Interceptor Pump Out Manifest
14	Grease Interceptor 'Certified' by Metro Water Services

Research Methodology

To fully understand the Foods Service Establishments approach to FOG prevention, twenty (20) Nashville restaurants completed a survey on the implementation and adherence to the Metro Water Services, Food Service Operations, and Grease Interceptor, Best Management Practices (BMPs). The twenty restaurants were a convenience sample and did not reflect a randomized sample of all restaurants in the city.

Food Service Operations BMP Survey Results

The first line of defense in preventing FOG entering the sanitary sewer system lies solely with FSEs Food Service Operations. By analyzing the survey data collected regarding Food Service Operations BMPs, a quick determination can be reached as to the FSEs' active participation towards FOG prevention. Food Service Operations BMPs were measured as to the percent 'active' across all twenty FSEs surveyed. As Figure 2 details, the results varied across each BMP, with some reaching a high percentage of 'active' status while others were nearly completely 'inactive.'

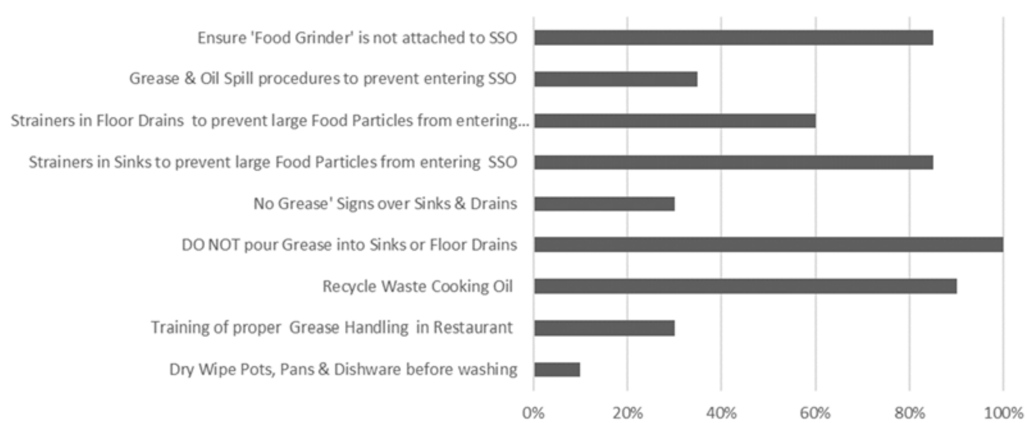

Figure 2: % of Active Food Service Operations BMPs across FSEs

To further understand the varied application of the Food Service Operations BMPs, Figure 3 displays the data as a percentage of 'active' BMPs by individual FSEs. This data provides a potential understanding of individual FSEs commitment towards the reduction of FOG. Additional research is warranted to determine the reasons for not implementing specific BMPs. In total, only an average of 58% of the Food Service Operations BMPs were active among the FSEs surveyed.

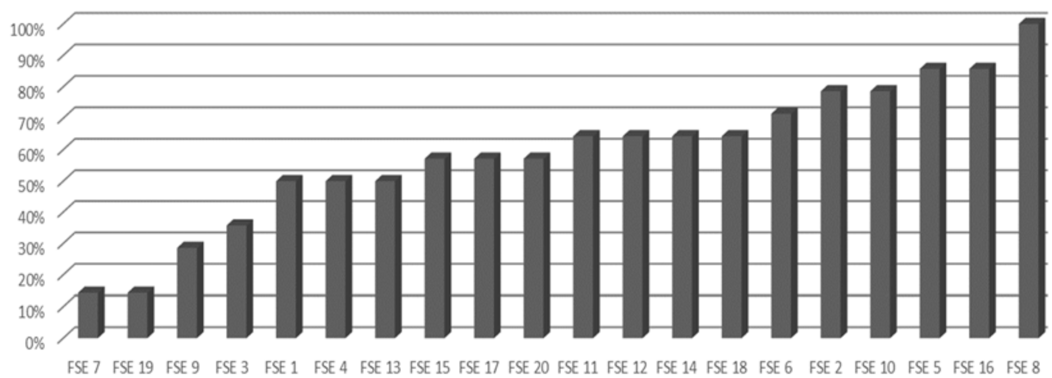

Figure 3: % of Active Food Service Operations BMPs by FSE

Grease Interceptor BMP Survey Results

The last line of defense in preventing FOG entering the sanitary sewer system lies solely with FSEs Grease Interceptor BMPs. By analyzing the survey data collected regarding Grease Interceptor BMPs, a quick determination can be reached as to the FSEs' active participation towards FOG prevention. Grease Interceptor BMPs were measured as to the percent *active* across all twenty FSEs surveyed. As Figure 4 details, the results varied across each BMP, with some reaching a high percentage of 'active' status while others were nearly completely 'inactive.'

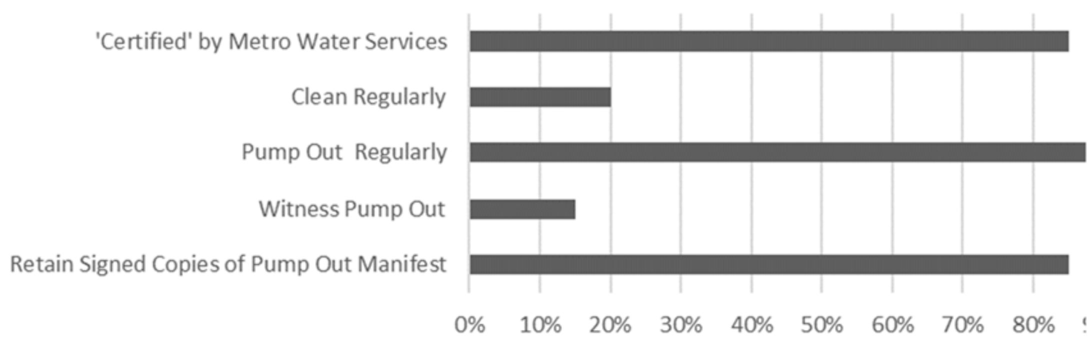

Figure 4: % of Active Grease Interceptor BMPs across FSEs

The percent of Grease Interceptor BMPs across FSEs demonstrates a high compliance to certification, pump out, and signed copies of pump out manifest, but a meager percentage of compliance to cleaning and witnessing the pump out. Further study may be needed to determine if this is due to not understanding the requirements versus only completing the items easily identified during random inspections. Additional data review of the percent of active grease interceptor BMPs by individual FSE demonstrates many are middle of the road with some at a high level of compliance. In contrast, several are not compliant at all. In total, only an average of 59% of the Grease Interceptor BMPs were active among the FSEs surveyed (see Figure 5).

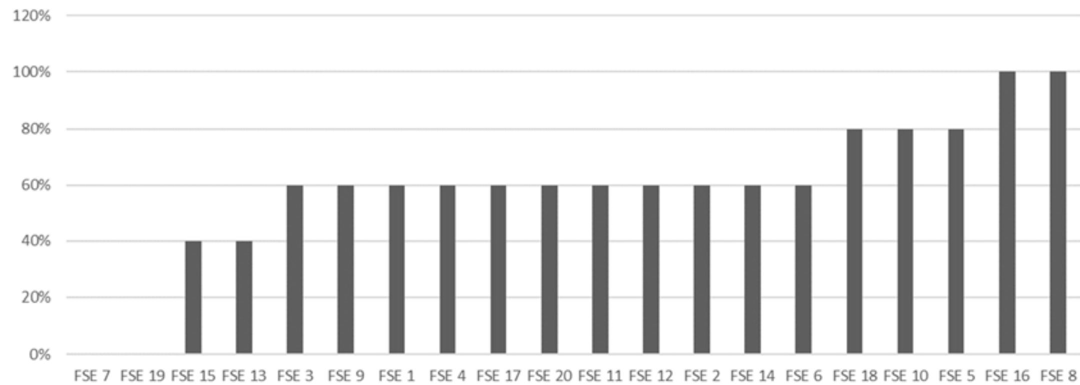

Figure 5: % of Active Grease Interceptor BMPs by FSE

Additional conclusions could also be reached that even with the static presence of the Grease Interceptor, Food Service Operations still plays a pivotal role in the effectiveness of this equipment. As Figure 6 illustrates, FSEs with a low percentage of active Food Service BMPs, are also prone to a lower percentage of active Grease Interceptor BMPs, resulting in FOG entering the Sanitary Sewer System. This data could even support the argument of the ordinance inspector being the actual last line of defense in holding FSEs accountable to the Grease Interceptor BMPs.

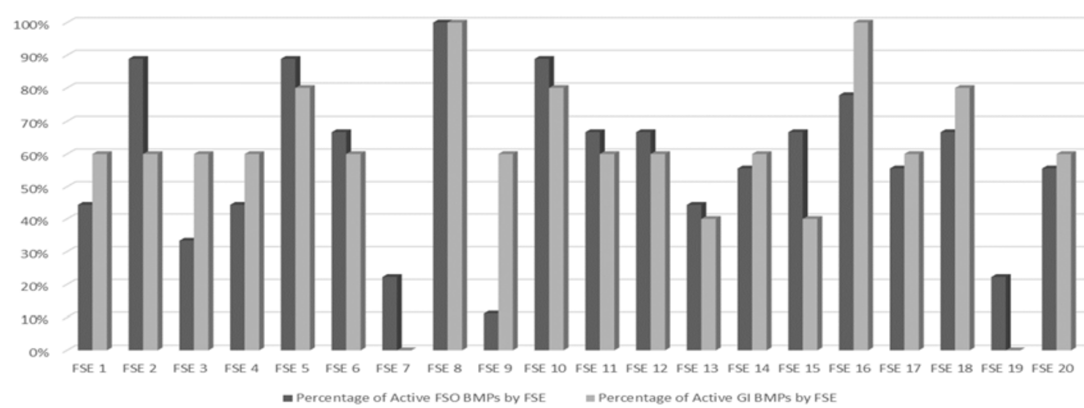

Figure 6: % of Active Grease Interceptor compared to Active Food Service Operations BMPs by FSE

Conclusion

Problems caused by wastewater from Food Service Establishments have served as the basis for ordinances and regulations governing the discharge of grease materials to the sanitary sewer system. This type of waste has forced just about every jurisdiction to require best management practices and installation of grease interceptors anywhere there is a commercial or industrial kitchen or any other FOG-producing activity going on (Sweet, 2008). As shown by the survey results, the following of BMPs established as the first line of defense by Food Service Establishments is sporadic. Further research may be necessary to determine the reasons, especially as compliance is tough to manage by local officials on a day to day basis. Therefore, this research concludes that Grease Interceptors are, in fact, functioning as the last line of defense in preventing FOG build-up and subsequent blockage of the sanitary sewer system.

References

40 CFR 403.5 - National pretreatment standards: Prohibited discharges. - Content Details - CFR-2002-title40-vol25-sec403-5. (n.d.). Retrieved June 28, 2020, from https%3A%2F%2Fwww.govinfo.gov%2Fapp%2Fdetails%2FCFR-2002-title40-vol25%2FCFR-2002-title40-vol25-sec403-5

FACTS and MYTHS Grease Interceptor by Max Weiss. (2007).

FOG Management Policy effective 07.01.14_stamped by Metro Clerk.pdf. (n.d.). Retrieved May 26, 2020, from https://www.nashville.gov/Portals/0/SiteContent/WaterServices/docs/environmental_compliance/FOG%20Management%20Policy_effective%2007.01.14_stamped%20by%20Metro%20Clerk.pdf

Gurd, C., Jefferson, B., & Villa, R. (2019). Characterization of food service establishment wastewater and its implication for treatment. Journal of Environmental Management, 252, 109657. https://doi.org/10.1016/j.jenvman.2019.109657

Hao, Z., Malyala, D., Dean, L., & Ducoste, J. (2017). Attenuated Total Reflectance Fourier transform infrared spectroscopy for determination of Long Chain Free Fatty Acid concentration in oily wastewater using the double wavenumber extrapolation technique. Talanta, 165, 526–532. https://doi.org/10.1016/j.talanta.2017.01.006

He, X., III, F. L. de los R., & Ducoste, J. J. (2017). A critical review of fat, oil, and grease (FOG) in sewer collection systems: Challenges and control. Critical Reviews in Environmental Science and Technology, 47(13), 1191–1217. https://doi.org/10.1080/10643389.2017.1382282

LitReviewOnTheEval.pdf. (n.d.). Retrieved June 9, 2020, from https://www.tceq.texas.gov/assets/public/compliance/compliance_support/regulatory/ossf/LitReviewOnTheEval.pdf

Mini TOC: Title 15—WATER, SEWERS AND OTHER PUBLIC SERVICES | Code of Ordinances | Metro Government of Nashville and Davidson County, TN | Municode Library. (n.d.). Retrieved June 28, 2020, from https://librarystage.municode.com/tn/metro_government_of_nashville_and_davidson_county/codes/code_of_ordinances?nodeId=CD_TIT15WASEOTPUSE

Nashville > Water Services > Environmental Compliance. (n.d.). Retrieved June 25, 2020, from https://www.nashville.gov/Water-Services/Environmental-Compliance.aspx

Sweet, J. (2008). Diversionary tactics: Grease interceptors protect sewer systems right on down the line. Reeves Journal, 2, 48.

Tennessee Guidance Doc.pdf. (n.d.). Retrieved May 28, 2020, from http://scap1.org/Collection%20Reference%20Library/Folder%20contains%20documents%20on%20Fats,%20Oils%20and%20Grease%20(FOG)/Tennessee%20Guidance%20Doc.pdf

USACE Southwestern Division: Construction Durations for Military Vertical Projects

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Delays with project completion and turnover is a global problem affecting construction and industry partners in many areas. These delays impact both planning and budgeting which are serious concerns for all stakeholders involved and difficult to resolve and overcome. The focus of this research paper is limited to only Military vertical construction projects executed by the Fort Worth District and specifically, the analysis of their associated construction durations. Construction performance data from the United States Army Corp of Engineers (USACE) SWF Primavera Project (P2) database was utilized in this study. The raw dataset covered the period of 2003 to 2021 and included a total of 4,435 projects. This dataset was reduced down to focus only on the 173 Military vertical construction projects executed by the USACE Fort Worth District and completed between the years of 2006 and 2020. The results of this research provide the USACE Project Delivery Team a better understanding of lessons learned and utilization of a more accurate method for establishing construction project durations for USACE projects.

Key Words: Construction duration, Period of Performance, Schedule, Military construction, Schedule delays

Introduction

Delays with project completion and turnover is a global problem affecting construction and industry partners in many areas. These delays impact both planning and budgeting which are serious concerns for all stakeholders involved and difficult to resolve and overcome. The competitive nature of the construction industry exerts pressure on contractors to keep project durations and costs as low as possible but the contract duration set by the client may not always be realistic and often result in delays to the project completion and added costs to the project. Construction projects in general are full of uncertainties, including weather, labor skills, site conditions, and management quality which all have the potential to impact the construction duration of the project. Accurately estimating the period of performance or duration of a construction project represents a critical factor for both the contractor and the stakeholder as well as the feasibility of the project. Currently within the Fort Worth District, there is not an established methodology or processes for estimating and establishing the planned construction period of performance or construction duration for a construction project.

The U.S. Army Corps of Engineers (USACE), Southwestern Division's (SWD) Military Mission spans four states: Texas, Louisiana, Oklahoma and Arkansas. Nearly one-fifth of the Nation's military activities are located within the Southwestern Division, covering nearly 440,000 square miles. The Division provides engineering, construction and environmental management services for 11 Army and 11 Air Force installations. They design and manage construction of new facilities, rehabilitate older facilities, and assist with installations' engineering challenges. The mission of the USACE SWD is to ensure soldiers have the best facilities possible for readiness andy training exercises and that they and their families are afforded an enhanced quality of life while serving our country (*Southwestern Division, U.S. Army Corps of Engineers*, n.d.).

The Southwestern Division has four District Offices located in Fort Worth, Texas; Galveston, Texas; Tulsa, Oklahoma; and Little Rock, Arkansas with the Fort Worth District office having the largest Military construction program of the four. The mission of districts is to ensure successful planning, programming, design, construction, maintenance and repair, and financial management for the facilities and real property located at their associated installations.

The focus of this research paper is limited to only Military vertical construction projects executed by the Fort Worth District and specifically, the analysis of their associated construction durations. In general, construction projects are full of uncertainties, including weather, labor skills, site conditions, and management quality that all can impact the construction duration of a project. Delays in construction projects, cost overruns and quality level issues have long been common problems in the construction and engineering sector (Larsen et al., 2016). The recent onset of the COVID pandemic that began in March 2020 and subsequent challenges with material and labor availability has added additional complexities to the art of estimating construction project durations. In the article, *Early Impacts of the COVID-19 Pandemic on the United States Construction Industry*, published in 2021 in the International Journal of Environmental Research and Public Health it was noted that "the construction industry experienced a number of adverse effects. These included material delivery delays, shortage of material, permitting delays, lower productivity rates, cash flow-related challenges, project suspension, price escalations, and potential conflicts and disputes." (Alsharef et al., 2021). Of which, many of these effects are still being realized by the construction industry in today's market conditions.

The United States Army Corps of Engineers utilizes the USACE Acquisition Instruction (UAI) manual which establishes uniform policies and procedures to ensure that business practices are consistent throughout USACE. It provides internal guidance, delegations of authority, assignments of responsibilities, procedures that are required by regulation to be established by the Head of the Contracting Activity (HCA), procedures that implement policies, and internal reporting requirements.(*Southwestern Division, U.S. Army Corps of Engineers*, n.d.). In addition to the UAI, the agency adheres to the Federal Acquisition Regulation (FAR), the Defense Federal Acquisition Regulation Supplement (DFARS), the Army Federal Acquisition Regulation Supplement (AFARS), or higher-level agency regulations in the execution of all contractual acquisitions.

A wide selection of contract types is available to the Government and contractors in order to provide needed flexibility in acquiring the large variety and volume of supplies and services required by agencies. There are many factors that the contracting officer should consider in selecting and negotiating the contract type (*FAR | Acquisition.GOV*, n.d.). Some of which include: price competition, price and cost analysis, type and complexity of the requirement, period of performance, acquisition history, availability of contracting mechanisms and contracting capacity. The contract types are grouped into two broad categories: fixed-price contracts and cost-reimbursement contracts. The typical contract type utilized by the USACE Fort Worth District for MILCON vertical construction projects is the fixed-price contract. A firm-fixed-price contract provides for a price that is not subject to any adjustment on the basis of the contractor's cost experience in performing the contract. This contract type places upon the contractor maximum risk and full responsibility for all costs and resulting profit or loss. It provides maximum incentive for the contractor to control costs and perform effectively and imposes a minimum administrative burden upon the contracting parties (*FAR | Acquisition.GOV*, n.d.). There are additional variations of this contract type that are available to the contracting officer but the basic firm-fixed-price contract type is the most utilized type by the USACE Fort Worth district for Military vertical construction projects. Within that type/category of contracts, the acquisition tools available and typically utilized by the district for MILCON construction projects include the following acquisition strategies: Design-Bid-Build, Design-Build, and Multiple Award Task Order Contract (MATOC) Task Order:

- The Design-Bid-Build acquisition strategy is a project delivery method in which the agency or owner contracts with separate entities for the design and construction of a project. The project design may be completed with in-house resources or by a separate contracting action for an Architect-Engineer to complete the design. Design-Bid-Build is considered the traditional method for project delivery.

- The Design-Build acquisition strategy employs an alternate acquisition strategy that shifts the majority of the risk to the construction contractor as they have full responsible for both the design and the construction of the project. With this acquisition strategy, the RFP includes a conceptual design (typically to ~35% design level) along with a scope of work that defines the mandatory performance requirements of the facility.

- The MATOC acquisition strategy is a combined variation of the DBB and DB acquisition strategies and is of advantage with decreased acquisition time due to the 'pre-selection' process of establishing a qualified pool of contractors for the type of project being solicitated, already being completed.

Research Objective

The accurate prediction for the period of performance or duration of a construction project represents a critical factor for both the contractor and the stakeholder as well as the feasibility of the project. This research paper studies the estimation and establishment of construction performance periods verses the actual time to complete the project for USACE Military vertical construction projects within Southwestern Division (SWD) of the U.S. Army Corps of Engineers. The focus of this research paper is limited to only Military vertical construction projects executed by the Fort Worth District and specifically, the analysis of their associated original or planned construction durations verses their actual time required to complete the projects.

One of the key mission goals of USACE is to *"Delivery What You Promise*". This sounds a lot easier than reality allows. As discussed earlier, construction projects are full of uncertainties, including weather, labor skills, site conditions, and management quality that all can impact the construction duration of a project. Delays in construction projects, cost overruns and quality level issues have long been common problems in the construction and engineering sector (Larsen et al., 2016). The goal of this research is to find applicable lessons learned from both Government and Industry partners and improve upon established processes in order to advance estimating methods for construction project durations for USACE Military vertical construction projects within Southwestern Division and more specifically for the Fort Worth District. This information would provide the Project Delivery Team a better understanding to lessons learned and utilization of a more accurate method for establishing construction project durations in order to improve project delivery and ultimately improve the organizational reputation by delivering projects as planned and promised.

Background and Literature Review

Various studies produced for the Government have highlighted poor prediction of client costs and construction duration period as key problems for the construction sector. Construction projects are widely seen as unpredictable in terms of delivery on time, within budget and to the standards of quality expected (Burrows et al., 2005). Construction projects in general are full of uncertainties, including weather, labor skills, site conditions, and management quality which all have the potential to impact the construction duration of the project.

Two critical performance indicators for any construction project are cost and duration. The construction contract cost and contract period of performance are often considered to be interconnected with impacts to one resulting with impacts to the other. Extensive research has proposed mathematical models to predict construction project durations based on regression analysis, Monte Carlo method (MCM), and the such. Yet regression analysis alone cannot capture the uncertainties within project execution and durations (Nguyen et al., 2013). Despite the close relationship between construction cost and duration, they are usually deemed as two contradictory objectives that need to be traded off in project management (Xiao et al., 2018). Various factors contribute to construction performance, including project complexity, financial considerations, political conditions, and market environments. Some are difficult to quantify because of the limited amount of data available (particularly at the early stage of construction), while other factors are difficult to incorporate due to limited knowledge of their explanatory relations, such as project communication and team hierarchical diversity. Consequently, predicting construction cost and duration is surrounded by considerable uncertainty; even the performance of projects with an identical design still differ because of these uncertainties (Xiao et al., 2018).

Contrary to cost overrun, the definition of time overrun is clearly articulated in literature. The most commonly used definition is the delay in time either beyond the agreed contract deadline or beyond the date the parties have agreed upon for the delivery of a project (O'Brien, 1976) or stated another way, a time overrun is an act or event that extends the time to perform the task beyond the agreed contract deadline. The level of success after project completion is not only based on time- and cost-based empirical criteria, but is also an individual weighing of time, cost and quality (Larsen et al., 2016) along with the level of customer satisfaction with the final product.

Walt Lipke developed a practice called earned schedule (ES) that results in time-based schedule performance metrics. These metrics are derived from standard earned value (EV) cost data. ES metrics are more intuitive in measuring schedule progress and more accurate in predicting schedule completion, than those of the limiting EV schedule metrics. A reality is that many schedules are not completely, if at all, resource/cost loaded. This creates a situation where ES or EV metrics can lead to questionable outcomes or cannot be used at all. Schedule activity duration data, however, is or should be readily available in all schedules (Crew, 2009).

In regards to contract changes and in terms of work execution, General Contractor project managers tend to keep two schedules: one for USACE to show no changes, and one for them to implement the items necessary to complete the changes and stay on schedule. This conflict creates a chance to introduce waste and error in the execution of the project. The intent for the General Contractor is to use the schedule as a management tool verses a reporting device. However, the demand to communicate compensation for unapproved work leads to a variety of schedule approaches by both the USACE and General Contractors (Gannon et al., 2012). According to Viles, et al., 2019, the main causes of construction project delays are problems that occur during execution, administrative problems and labor conflicts. The problems experienced during execution of the construction phase are typically based on unpredictable events, while administrative problems are typically rooted in communication issues and poor cash flow. A further breakdown of the issues experienced during the execution phase of a project relate to changes during construction, poor construction management, construction errors, economic/financial factors, conflict/personality clashes and lack of experience. (Viles et al., 2019).

The COVID pandemic which began in March 2020 added additional complexities to the art of estimating construction project durations due to challenges with construction materials, construction supply chain, contract administration, construction project management, changes to the working environment, health and safety management and the finances of construction organizations and individual employees of the construction industry (Ogunnusi et al., 2021).

Research Methodology

Construction performance data from the USACE SWF Primavera Project (P2) database was used in this study. The dataset covered the period of 2003 to 2021 and included a total of 4,435 projects. This dataset was reduced down to focus only the 173 Military vertical construction projects executed by the USACE Fort Worth District and completed between the years of 2006 and 2020. The detailed dataset was established as follows:

- The study is based on 173 construction projects completed within the USACE Fort Worth District Area of Responsibility (AOR) between 2006 and 2020.
- New construction and infrastructure projects were included.
- All acquisition types were considered i.e. no projects were eliminated from the dataset based on acquisition type.
- Projects for which some of the project variables were missing were excluded.
- Refurbishment, and repair and maintenance projects were excluded.
- Projects with significant changes to scope of work or uncontrollable delays were reviewed and potentially eliminated from the dataset.

Building construction duration was defined as the period of time between the date of the construction contract notice to proceed and the date of substantial completion. The original or estimated period of performance (PoP) or estimated construction duration was established as the difference between the original contract required completion (CRCD) date and the actual notice to proceed (NTP) date. [PoP = CRCD – NTP]. The actual period of performance or actual construction duration was established as the difference between the actual construction contract completion (CCD) date and the actual notice to proceed date (NTP). [Actual PoP = CCD – NTP].

The data from SWD USACE Information Systems database was analyzed and reduced down to 173 Military vertical construction projects specific to the Fort Worth District. The programmed amount of the projects ranged from ~$1M to $630M. The constructed facility types included barracks, maintenance facilities, administrative operations facilities, medical facilities, and child care facilities to name a few. Focus group discussions with personnel from Fort Worth District Programs and Project Management Division and Construction Division were conducted to determine the existing methodology and processes being applied in estimating and establishing the original planned construction period of performance or construction duration for a planned project. The Fort Worth District Small Business Office hosted two Virtual Industry Days showcasing upcoming projects at one of the installations served by the district to engage industry partners and obtain feedback to some of the challenges of today's market and manpower conditions. The first one was on 28 June, 2022 and the second one on 28 July, 2022. The participants included over 100 industry-related partners at each venue with a follow-on Q&A session to gauge industry's input into the challenges with establishing realistic construction durations with recent economical, manpower, and supply issues. The initial feedback was more generalized and limited to typical public concerns with the problems of increased material and labor costs but no real discussion of the solution(s) or how to gauge/apply risks appropriately.

Further data collection, input from industry partners and analysis is required in order to come to a reasonable conclusion of the impact and solution to this issue.

Data Analysis

Results of the focus group discussions with personnel from Fort Worth District Programs and Project Management Division and Construction Division revealed that there was no uniform methodology or processes between district offices with estimating and establishing the planned construction period of performance or construction duration for a planned project. The Project Delivery Team, lead by the project manager typically just utilized previous experience with input from the local construction office and installation personnel to establish the planned construction period of performance.

Construction performance data from the USACE SWF Primavera Project (P2) database was analyzed for 173 Military vertical construction projects completed between the years of 2006 and 2020. The programmed amount of the projects ranged from ~$1M to $630M. The constructed facility types included barracks, maintenance facilities, administrative operations facilities, medical facilities, and child care facilities to name a few. The projects that had significant scope changes and/or contractual modifications were removed from the data set to remove any outliers from the analysis. The original or estimated period of performance (PoP) or estimated construction duration was established as the difference between the original contract required completion (CRCD) date and the actual notice to proceed (NTP) date. [PoP = CRCD – NTP]. The actual period of performance or actual construction duration was established as the difference between the actual construction contract completion (CCD) date and the actual notice to proceed date (NTP). [Actual PoP = CCD – NTP].

Figure 2 displays the actual construction duration verses the predicted construction duration for the MILCON vertical construction projects analyzed from the USACE SWF P2 database. The original construction durations and actual construction durations were calculated from established contractual dates and analyzed for time growth for 173 projects. Figure 3 displays the time growth for these same projects.

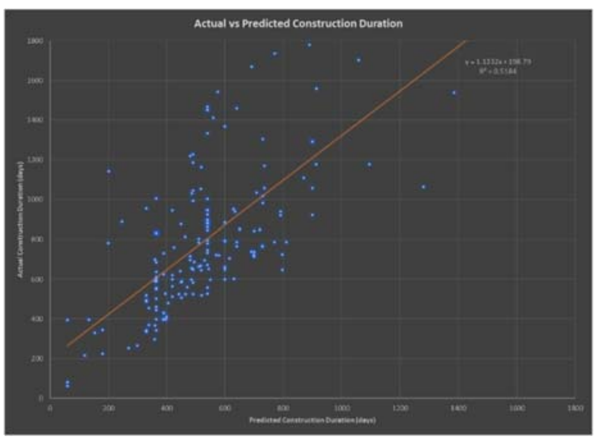


Figure 2. Actual vs Predicted Construction Duration

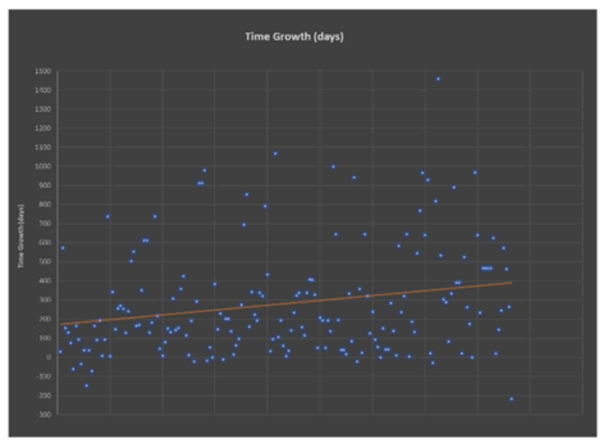


Figure 3. Construction Time Growth of 173 MILCON Projects within Ft. Worth District between 2006-2020

The analysis of time growth for the 173 projects resulted with an average of an additional 282 days being added to the construction duration. Of the project data analyzed, ten (10) of the projects completed ahead of schedule (early), three (3) of the projects completed on time as originally scheduled (on time), and 160 projects completed behind schedule (late).

The project construction durations were also analyzed based on location or Area of Responsibility (AOR). As noted above, the average time growth across the projects analyzed for the district was the addition of 282 days to the construction duration. The analysis of the individual installations revealed that five (5) of the 13 installations were above the average time growth for the district, with the top two culprits being Fort Hood and Joint Base San Antonio. Although, as would be expected due to the fact that these two installations had the majority (>50%) based on the number of projects analyzed and over 76% of total costs for all projects. Reference Appendix A and Appendix B for detail charts and analysis associated with each of the below noted areas of responsibility. For example, referencing the below table and charts in Appendix A, we see that the average time growth for the projects analyzed at Fort Hood, Joint Base San Antonio, and Fort Polk were 260 days, 327 days, and 366 days, respectfully. Also, with reference to the pie charts in Appendix B, you can see that the light blue wedge of the pie represents projects at Fort Hood, which had 44 of the total projects analyzed or 25% of the total but only had 23% of the overall total time growth. The dark grey piece on the left side of the pie charts represents Joint Base San Antonio which had 58 projects or 33% of the total projects but actually carries 39% of the total time growth. The green wedge of the two pie charts to the bottom right represents Fort Polk which had 17 of the projects analyzed or 10% of the total projects analyzed and accounted for 13% of the total time growth. The breakdown by installation or AOR was analyzed as shown in the below table.

No. of Projects	Location	Avg. Time Growth (days)	% Total Projects	% Total Time Growth	PA ($M)
1	Camp Bullis	31	0.58	0.06	1.6
2	Corpus Christi Army Depot	363	1.16	1.49	25.1
2	Dyess AFB, TX	103	1.16	0.42	25.0
19	Fort Bliss	123	10.98	4.78	875.5
44	Fort Hood	260	25.43	23.49	1,834.5
17	Fort Polk	366	9.83	12.77	188.4
5	Fort Sam Houston	95	2.89	0.98	57.6
7	Goodfellow Air Force Base	298	4.05	4.28	92.9
58	Joint Base San Antonio	327	33.53	38.87	3,443.2
3	Lackland Air Force Base	146	1.73	0.90	71.7
8	Laughlin Air Force Base	542	4.62	8.90	24.6
1	Randolph Air Force Base	19	0.58	0.04	36.0
6	Red River Army Depot	246	3.47	3.03	192.3
173	**Total No. of Projects**				

Figure 4 contains the additional data of the programmed amount ($M) associated with each project that was reviewed but there was no real correlation or indication discovered that the cost of the project had any impact to the associated time growth of that project.

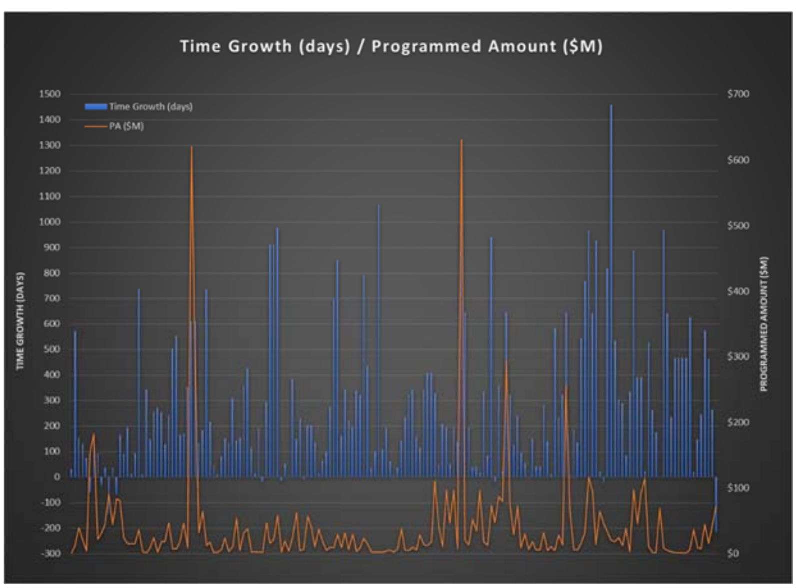


Figure 4. Construction Time Growth (days) and Programmed Amount ($M)

Conclusions and Future Research

Construction projects in general are full of uncertainties, including weather, labor skills, site conditions, and management quality which all have the potential to impact the construction duration of the project. There are many variables to this equation and there is no right or wrong answer to this question. One can only apply knowledge and experience in order to formulate an educated prediction based on conditions at the time of project solicitation / award. Based on the results of this analysis, industry input, and focus group discussions it is recommended that the Project Delivery Team apply historical lessons learned from projects with similar magnitude and complexities along with the knowledge of parameters within the area of project execution be considered and applied when establishing and estimating the construction duration for any construction project.

The impacts to the construction industry imposed by the COVID pandemic of 2020-2021 are still be realized today through labor and material shortages as well as continued supply chain delays. Of which, the impacts to project durations for MILCON vertical construction projects that are still within the execution phase of construction within the USACE Fort Worth District have not yet fully been realized and will most likely result with a prolonged recovery period and/or establish a new normal for the construction industry. The full impacts to the construction industry and public sector from the COVID pandemic may not be apparent for several years yet to come but will most likely result with a path of carnage and everlasting scars imposed on all who shared and suffered the Pandemic's wrath. In view of the enormity of influence that the COVID pandemic had on the global construction industry, there is a need for further investigation into the impacts experienced and future implications to the construction industry. Additionally, further analysis of data related to the contract type, project location, local subcontractor/manpower availability, and geographic area may further enhance the accuracy with establishing construction project durations within a more acceptable field of error.

References

Alsharef, A., Banerjee, S., Uddin, S. M. J., Albert, A., & Jaselskis, E. (2021). Early Impacts of the COVID-19 Pandemic on the United States Construction Industry. *International Journal of Environmental Research and Public Health*, *18*(4), 1559. https://doi.org/10.3390/ijerph18041559

Burrows, T. K., Pegg, I., & Martin, J. (2005). Predicting Building Construction Duration. *AACE International Transactions*, 14.1-14.9.

Crew, S. W. (2009). Activity Duration Based Schedule Progress and Prediction Metrics. *AACE International Transactions*, EVM.03.1-EVM.03.11.

FAR | Acquisition.GOV. (n.d.). Retrieved July 23, 2022, from https://www.acquisition.gov/browse/index/far

Gannon, T., Feng, P., & Sitzabee, W. (2012). Reliable Schedule Forecasting in Federal Design-Build Facility Procurement. *Lean Construction Journal*, 1–14.

Larsen, J. K., Shen, G. Q., Lindhard, S. M., & Brunoe, T. D. (2016). Factors Affecting Schedule Delay, Cost Overrun, and Quality Level in Public Construction Projects. *Journal of Management in Engineering*, *32*(1), 04015032. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000391

Nguyen, L. D., Phan, D. H., & Tang, L. C. M. (2013). Simulating Construction Duration for Multistory Buildings with Controlling Activities. *Journal of Construction Engineering & Management*, *139*(8), 951–959. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000677

O'Brien, J. J. (1976). *Construction delay: Responsibilities, risks, and litigation* (LADC Auburn KF902 .O27). Cahners Books International.

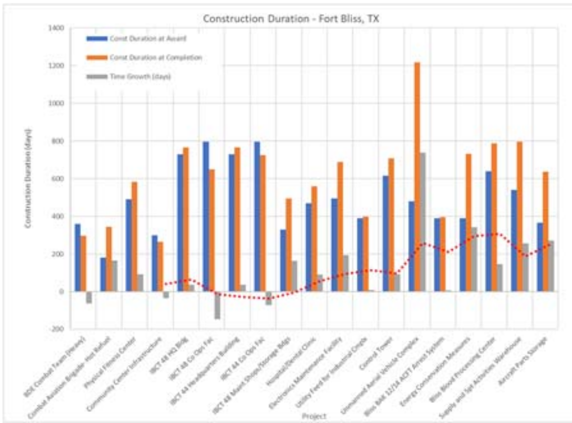
Ogunnusi, M., Omotayo, T., Hamma-Adama, M., Awuzie, B. O., & Egbelakin, T. (2021). Lessons learned from the impact of COVID-19 on the global construction industry. *Journal of Engineering, Design and Technology*, *20*(1), 299–320. https://doi.org/10.1108/JEDT-05-2021-0286

Southwestern Division, U.S. Army Corps of Engineers. (n.d.). Retrieved June 20, 2022, from https://www.swd.usace.army.mil/

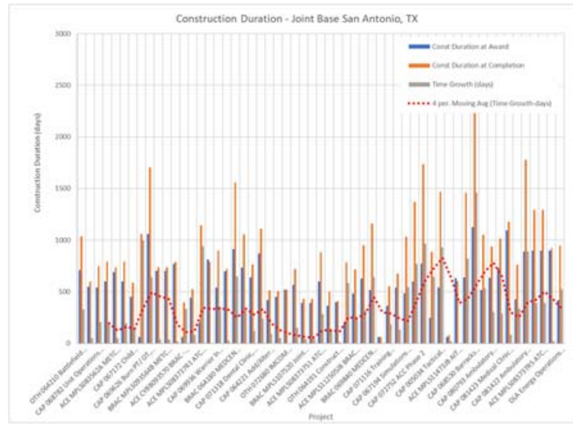
Viles, E., Rudeli, N. C., & Santilli, A. (2019). Causes of delay in construction projects: A quantitative analysis. *Engineering, Construction and Architectural Management*, *27*(4), 917–935. https://doi.org/10.1108/ECAM-01-2019-0024

Xiao, X., Wang, F., Li, H., & Skitmore, M. (2018). Modelling the stochastic dependence underlying construction cost and duration. *Journal of Civil Engineering and Management*, *24*(6), 444–456. https://doi.org/10.3846/jcem.2018.5712

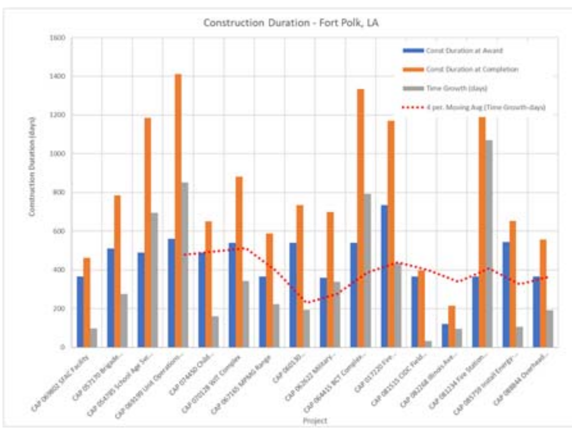
Appendix – A
Construction Duration and Time Growth at Individual Installations



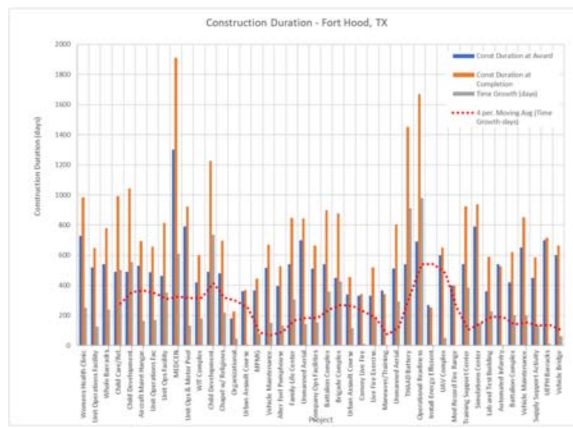
Construction Duration – Fort Bliss, TX



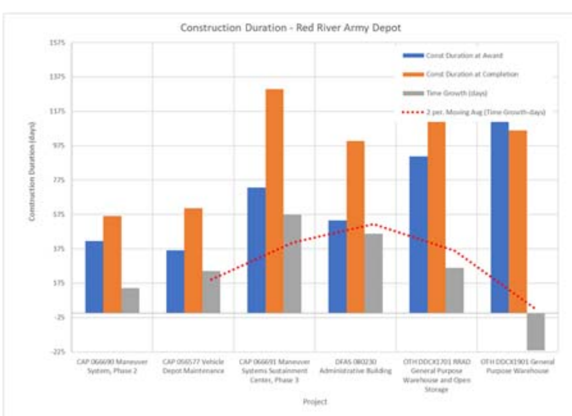
Construction Duration – Joint Base San Antonio, TX



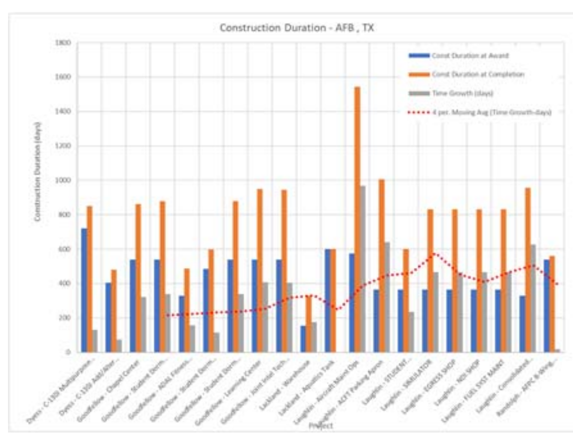
Construction Duration – Fort Polk, LA



Construction Duration – Fort Hood, TX

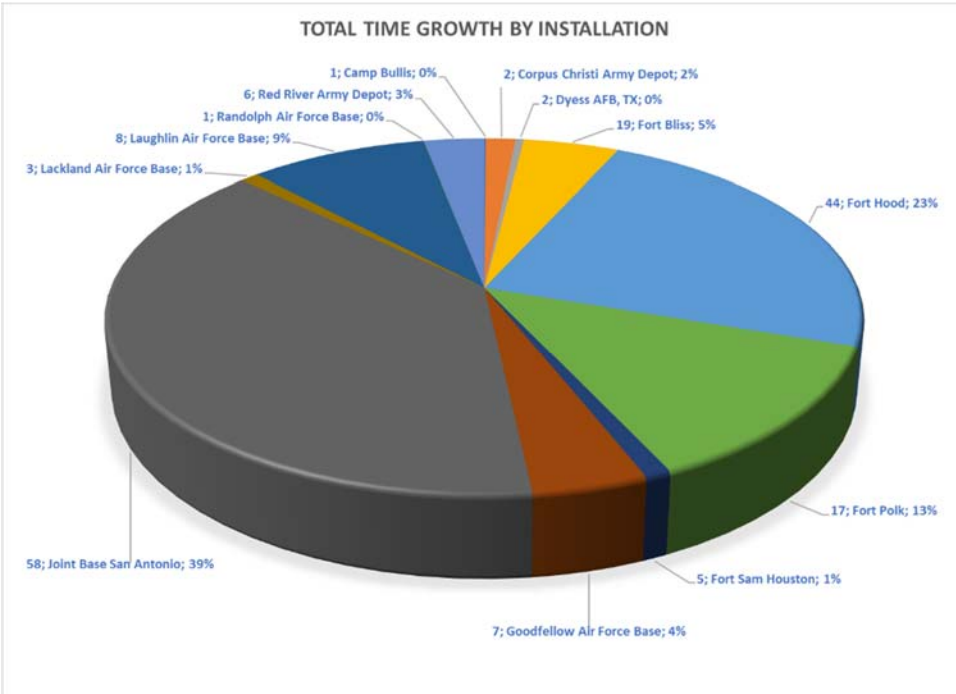


Construction Duration – Red River Army Depot

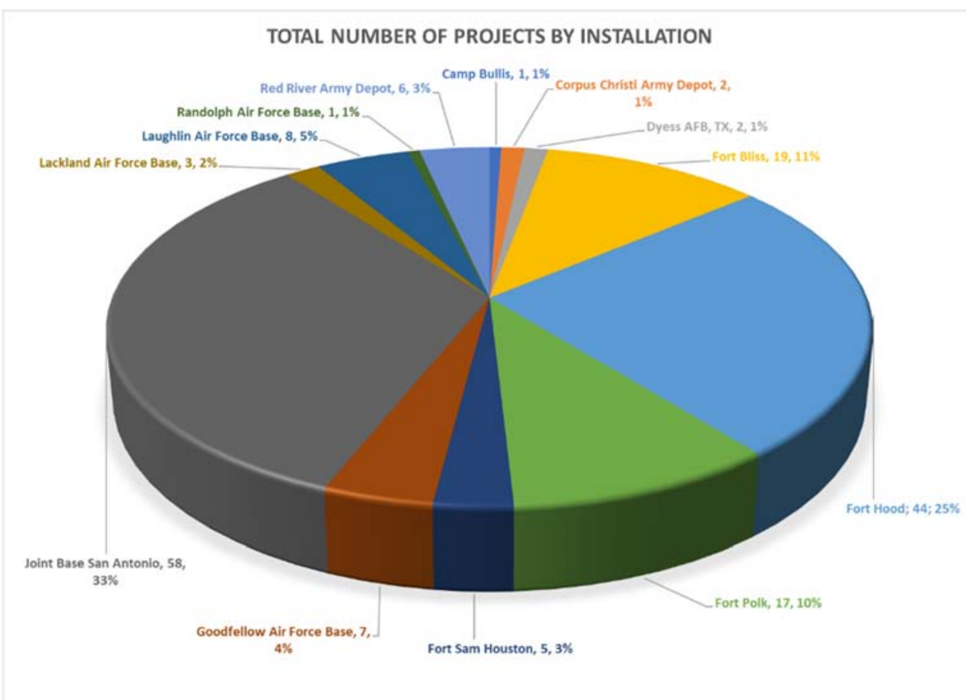


Construction Duration – Various AFB, TX

Appendix – B
Time Growth and Total Projects by Installation



Total Time Growth by Installation (# Projects; Location; % of Total Time Growth)



Total Number of Projects by Installation (Location; # Projects; % of Total Projects)

Investigation of Cost Data Management Practices in the U.S. Construction Industry

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Organization and use of data is crucial for a construction company to serve clients in this fast-paced, technology driven world; however, many may not consistently leverage their past bid and completed project data. The purpose of this study was to review and identify present trends and issues in project cost data management processes and to understand what data sharing approaches currently exist within construction companies. The study involved a survey distributed to construction professionals across the United States. A total of 186 survey responses revealed most were trained very little, or not at all, on how to transfer data from estimating software to job cost tracking software. Historical cost data from both successful and unsuccessful bids is typically kept by estimators for use when developing future estimates. This cost data is typically not aggregated into one location, though. Aggregating historical cost data is important and laborious. If data is aggregated, it is done so infrequently and inconsistently. Lastly, many companies do not have a transparent protocol for managing and aggregating data from past projects. The findings of this study are useful for construction practitioners, as well as researchers and construction management educators.

Key Words: Data management, Cost, Estimating, Software, Project management

Introduction and Literature Review

The explosion of revolutionary technologies available to the construction industry has presented opportunities and challenges for companies of all sizes. Some companies have been faster than others to adopt and replace the traditional use of manual processes such as using paper and pencil (Abu Awwad et al., 2020; Pellicer et al., 2012). Nonetheless, leveraging computers and their various software platforms to complete daily tasks is standard in almost every industry today, including construction.

The marketplace for construction cost management software is vast, sometimes difficult to navigate, and ever changing. A simple search engine query into “best construction software” will provide a myriad of options, including established platforms, and new up-and-coming solutions. Interestingly, instead of utilizing newer software to build and manage project cost estimates, contractors continue to use two that have been on the market for over thirty years: Microsoft Excel and Sage Estimating

(Collins & Redden, 2022; JB Knowledge, 2020). Both are considered clunky and static with considerable front-end, manual processing time required to conduct data extraction and/or data transfer with newer project management software. Building Information Modeling (BIM) is considered another data-rich technology that has broadly lagged in leveraging cost data for many contractors (Gholizadeh et al., 2018; Karan and Irizarry, 2015). Abu Awwad et al. (2020) identified multiple human factors, organizational factors, process factors, and external factors to be critical in successful BIM implementation in the United Kingdom construction industry. Many construction companies have not yet moved into maximizing newer technology, such as BIM, for cost control (Smith, 2014). Another shift within the last decade is the profuse use of mobile devices, drones, augmented reality technologies, photography, and video sites for both estimating and project management. As a result, various applications have gained traction to reach various stakeholders through multiple channels. The numerous platforms and applications dedicated to project communication, documentation, cost management and accounting creates a plethora of data (Igwe et al., 2019; Martínez-Rojas et al., 2015).

While the application of data analytics in the construction industry is not new, one main obstacle is that while there is abundant data to leverage, all are in different platforms and in different forms (Philip Chen & Zhang, 2014; Lu et al., 2016). The need to deal with different types of data has caused companies to yearn for practical, efficient, and seamless data management techniques. Huang et al. (2021) asserted the construction industry is facing a "data tsunami" and conducted a metanalysis of challenges of data-driven construction project management in the Big Data context. Bilal et al. (2016) found the "adoption of Big Data technologies in the construction industry remains at a nascent stage and lags the broad uptake of these technologies in other fields."

Historical project data plays a specific, vital role for contractors of all sizes to apply when securing and managing new projects (Adbelaty et al., 2022; Abdelaty et al., 2020; Cheng et al., 2012) Previous work by Abdelaty et al. (2022) developed a data-driven approach from one company's historical bid day data from the past 45 years. The research particularly targeted serving small and medium-size contractors with a framework to leverage historical bid data for use in conceptual estimates. Liu et al. (2012) found historical means proved more advantageous over a multiple linear regression predictive model approach for formulating preliminary engineering budgets for new roadway projects. Cost estimates often require the consideration of historical data on construction costs to accurately estimate costs of future projects. Historical cost data only benefits a company's cost estimation efforts when the data is gathered and organized for future applications.

To summarize, data has become an important resource for a company in today's world. Given the digital shift society has been making and the continuous growth of data, construction companies desire to be data-driven. The estimating and bidding (i.e. tender) process for each construction company produces a plethora of critical data. The utilization of said data is currently in a state of disarray for many. Choosing a suitable method, or protocol, for efficiently storing, processing, and managing data from numerous sources remains challenging for contractors of all sizes. Previous research is focused on creating or suggesting models for companies to potentially implement to harvest cost data. This research stepped back to examine the overall current position of cost data management in construction firms in the United States.

Research Methodology

The purpose of this study was to review and identify present trends and issues in project cost data management processes and understand what data sharing approaches, particularly from estimating to operations, currently exist within construction companies in the United States. The authors partnered with the American Society of Professional Estimators (ASPE) to conduct this research, as the association has a substantial and experienced membership representing firms across the United States. ASPE is made up of five geographic regions, with over 50 chapters throughout those regions. The exact number of individual members was not provided to the authors by ASPE, but the ASPE website states that the group has over 6,200 members.

The authors first conducted thorough research to identify estimating and project cost management platforms on the current market (Collins and Redden, 2022). The authors then established inquiries regarding the various identified platforms and the management protocols for data derived from those various identified platforms. For this phase of the research, an online survey instrument was developed in Qualtrics by the authors, the contents of which were validated by a group of experienced construction professionals in the ASPE leadership. The survey investigated the following themes regarding data, along with questions on basic demographic information:

1. Process of Transferring Data from Estimating to Operations
2. Storing, Managing and Use of Historical Cost Data

The survey was sent out via email to the ASPE membership once during November of 2019, and twice during December of 2019. Concurrently, the survey was also sent out to members of the Auburn University McWhorter School of Building Science industry advisory committee. Both surveys were closed in January of 2020.

Results and Discussion

The authors received 186 complete survey responses, which included 144 ASPE members, and 42 industry advisory committee members. The respondents had an average of 28 years of construction industry experience and were in 35 of the 50 states. The respondents average over seven estimates/budgets completed each month with an average cost between $1 million and $10 million. A wide range of market segments were represented in the respondents' company portfolios. Table 1 provides a breakdown of respondent firm types. As shown, approximately half of the respondents represented general contracting firms, followed by consulting and specialty contractors/subcontracting firms.

Table 1
Breakdown of company types represented in survey responses

Firm Type	Total Responses
General Contractor	95 (51%)
Consultant	41 (22%)
Specialty Contractor/ Subcontractor	20 (11%)
Owner/ Client	13 (7%)
Design Firm/ Architect	9 (5%)
Unknown	8 (4%)

The Process of Transferring Data from Estimating to Operations

A couple of questions in the survey investigated the process of data transfer from estimating to the project cost control in project management systems which is traditionally known as an operations function in the United States. As stated previously, the literature identified Microsoft Excel and Sage Estimating as the most widely utilized software for creating, managing and/or finalizing project estimates (Collins & Redden, 2022; JB Knowledge, 2020). This study investigated the software used for project cost management after the project award. Interestingly, the responses were scattered amongst various software programs currently available. Respondents frequently deviated from Microsoft Excel in their project cost management software. While some (less than 15%) did report continuing to use Microsoft Excel for project cost management, many respondents confirmed their company shifts, or transfers, the estimate cost data into one of the following: Procore, Trimble ProjectSight, Sage 300, CMiC, and/or Trimble Viewpoint. Proprietary, or a company customized product, was also mentioned by a few respondents.

Table 2 provides a summary of responses regarding how much time is spent transferring estimate data to operations for one project. The survey also inquired about the job title or role within the company who is responsible for conducting the transfer. The duty of transferring data from estimating to the operations is split between Project Managers (48%) and Estimators (33%). Other represented 19% of the responses and included roles identified as accounting personnel such as Chief Financial Officer (CFO), Job Cost Analyst, or Cost Controller. Over half (57%) stated the amount of time currently spent transferring estimate data to operations for a single project is two hours or less.

Table 2

On average, how much time is spent transferring estimate data to operations data for one project?

Less than an hour	26%
1-2 hours	31%
2-4 hours	19%
More than 4 hours	24%

A combination of manual entry and import/export functions of spreadsheets was the most common way of handling the movement of data from estimating to operations. When respondents had an open-ended question to explain their protocol, most protocols place the responsibility on one or a select few employees to do the transfer. 46% of responses acknowledged there are issues with data transfer. The most common issues according to respondents involve (1) inconsistent code costs, (2) knowledge loss in the transfer, (3) human errors, (4) software integration issues, (5) missing or duplicate information, and (6) speed and accuracy of transfer.

Figure 1 provides a summary of responses regarding what the amount of training the survey respondents received as part of the role in the preconstruction area of their construction business. Most estimators (over 66%) were trained very little, or not at all, on how to transfer data from estimating software to job cost tracking software.

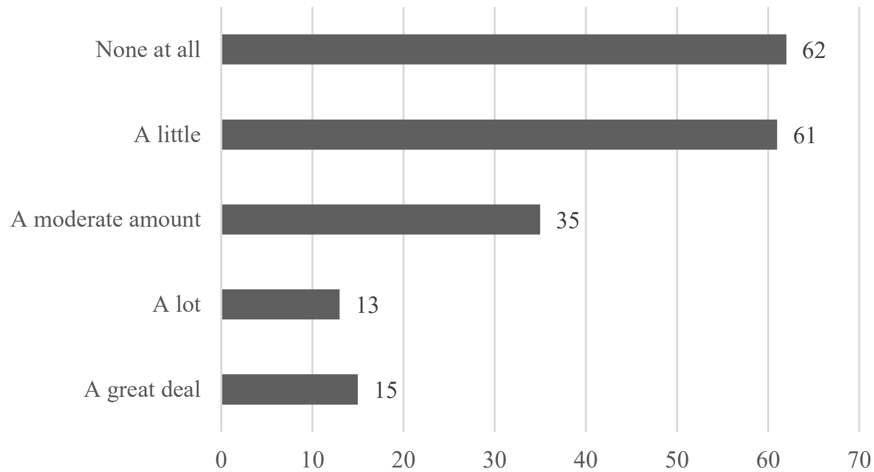

Figure 1. Survey Responses Regarding Amount of Training Received on Data Transfer from Estimates to Job Cost

Storing, Managing and Utilizing Historical Cost Data

Table 3 provides a summary of responses regarding the choice to store historical cost data. Historical cost data from both successful and unsuccessful bids is typically kept by estimators for use when developing future estimates. Survey respondents were able to Out of the 186 total respondents, 118 (63%) answered all project data is retained for completed projects, and 101 (54%) answered the data on bid but not awarded projects, noted as Bid Only Projects (not awarded), is also kept. Thirty-four respondents (18%) reported not keeping project estimate data for Bid Only Projects which would be projects the company bid but did not move to building the project.

Table 3

Survey Responses Regarding Preserving Historical Costs Data

	Completed Projects	Bid Only Projects (Not Awarded)
Yes, all project data is kept	118	101
Yes, but data only on some projects is kept	54	51
No, project data is not kept	14	34
Total	186	186

One respondent offered further explanation by adding in an optional text entry box for this question, “While all project data (won and lost) is archived, only select projects are aggregated and used to generate historic data. Projects are selected based on complexity, detail of estimate, and project sector. Actual cost data is also tracked on all current and completed work.”

Table 4 provides a summary of responses regarding the location(s) a company stores historical cost data. Choices in the survey for this question included local computer hard drive, accounting software platform, estimating software platform, server accessible to estimating staff only, server accessible to all company employees, and "the cloud." Respondents were asked to check all that apply for storage location of historical cost data. Multiple choice selection per survey respondent was common for this question. The most common location for storing the company historical cost data is on a server. Software platforms, both estimating and accounting platforms, were the least utilized locations for storing historical cost data.

Table 4

Survey Responses Regarding Storage Location(s) of Historical Cost Data

	Completed Projects	Bid Only Projects (Not Awarded)
Accounting software platform	35	5
“The Cloud”	46	37
Estimating software platform	22	20
Server accessible to all company employees	54	47
Server accessible to estimating staff only	47	57
Local computer hard drive	41	35

Respondents were asked, “Does your company have a protocol for managing and aggregating data from past projects?” Many companies do not have a protocol for managing and aggregating data from past projects, but some do, and some are working to develop one. One hundred eighty-one (181) respondents answered the question, “Does your company aggregate data from past projects into one location?” A total of 124 responded (68%) that this data is not aggregated into one location while the other 32% said their company does aggregate data into one location. Multiple respondents added further explanation in an optional text entry box offered with this question and stated, “no set protocol; differs between offices and market sectors.”

The frequency of updating the aggregated data was also investigated. Of the 186 validated survey responses, 110 responded to the question, “How often is this aggregated data updated?” Figure 2 provides a summary of responses regarding how often the aggregated data is updated. Fifty-three percent (53%) state any aggregated data is updated yearly or even less frequently (rarely and never), while only 39% (or 43 respondents) state aggregated data is updated on a quarterly or monthly basis.

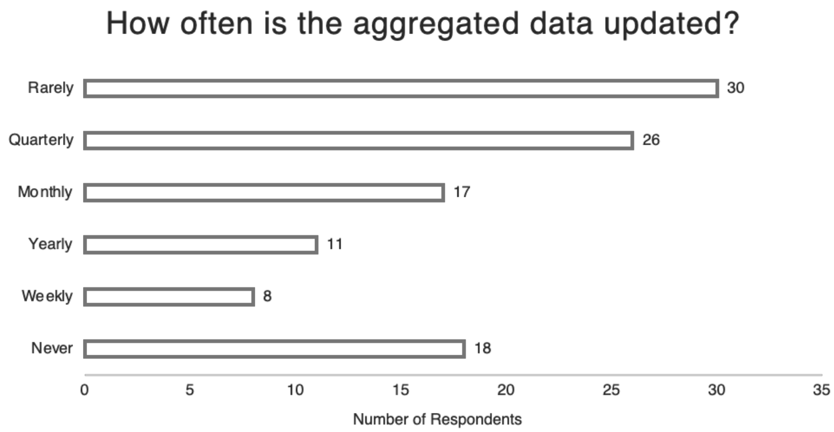

Figure 2. Survey Responses Regarding Frequency of Aggregated Data Updates

Lastly, the question was asked of each individual survey participant regarding their own use of past project data. The survey question was written as follows: “Do you personally use data from past projects when developing estimates for new projects?” Fifty percent (50%) of respondents stated only sometimes/selectively, while 44% said they always use data from past projects, and 6% stated they never use data from past projects when developing estimates for new projects.

Conclusions, Limitations, and Future Research

With all the advance of various technologies, one major challenge for contractors is the strategy for organization, management and administration of project cost continues to be complicated and cumbersome. The purpose of this study was to review and identify present trends and issues in project cost data management processes and understand what data sharing approaches, particularly from estimating to operations, currently exist within construction companies in the United States. Individuals associated with ASPE and the school’s industry advisory council were surveyed.

Less than 15% of respondents report continuing to use the same software utilized in the estimating and bidding phase which is most commonly Microsoft Excel. Most respondents confirmed their company shifts, or transfers, the estimate data into one of the following: Procore, Trimble ProjectSight, Sage 300, CMiC, and/or Trimble Viewpoint. A few companies have a proprietary or a company customized product for cost control and management in the operations phase of project. This shift in software, or data transfer, can cause issues in producing a seamless, coherent data exchange and lacks in the ability for quick, critical data sharing.

Historical cost data from both successful and unsuccessful bids is typically kept by estimators for use when developing future estimates. Although, construction firms tend to lean on manual project estimate data retrieval processes and ad-hoc decision making from senior-level roles in the company, such as Chief Estimators and Project Executives, for when and what information is aggregated for historical cost data reference. Another significant finding of this study is that when companies do collate their bid project and completed project cost data, the frequency in updating the aggregated data location is subpar at best. More than half of respondents (53%) do not have procedures in place to update the aggregated database in a timely manner to leverage that data in their work consistently.

This causes irregularity and confusion in the information for the broader employee base since it is unknown what factors are elected in such analysis (Adbelaty et al., 2022).

The results described are limited to the pool of voluntary respondents associated with ASPE and the school's industry advisory council. Similar results may or may not be found if a different sample was used. Future research should continue to assess where construction companies can improve their data management and data analytic processes. Performing even finer grain analytics across construction departments seems virtually impossible for some currently, which is the key to effectiveness, accuracy, and high return-on-investment (ROI) for the company. Researchers through this study have a broad base understanding of the current issues and trends in data management, particularly from the preconstruction lens to transferring into the project management lens. Next steps may include finding easy and effective solutions for companies of all sizes to improve the "data tsunami" as Huang et al. (2021) stated that construction companies currently are confronting today.

References

Abdelaty, A., Nessalhauf, K., & Munie, N. (2022). Using historical bid data for enhanced conceptual estimating. *In Proceedings of the 58th Annual Associated Schools of Construction International Conference, EPiC Series in Built Environment*, 3, 192-199. https://doi.org/10.29007/7x4j

Abdelaty, A., Shrestha, K.J., & Jeong, H.D. (2020). Estimating preconstruciton services for bridge design projects. Journal of Management in Engineering, 36(4). https://doi.org/10.1061/(ASCE)ME.1943-5479.0000793

Abu Awwad, K., Shibani, A., & Ghostin, M. (2020). Exploring the critical success factors influencing BIM level 2 implementation in the UK construction industry: the case of SMEs. *International Journal of Construction Management*, 22(10), 1894-1901. https://doi.org/10.1080/15623599.2020.1744213

Bilal, M., Oyedele, L., Qadir, J., Munir, K., Ajayi, S., Akinade, O., Owolabi, H., Alaka, H., Pasha, M. (2016). Big Data in the construction industry: A review of present status, opportunities, and future trends. *Advanced Engineering Informatics*, 30(3), 500-521. https://doi.org/10.1016/j.aei.2016.07.001

Cheng, T., Wang, Y., & Sun, Y. (2012). Development and application of tender evaluation decision-making and risk early warning system for water projects based on KDD. *Advances in Engineering Software*, 48, 58–69. https://doi.org/10.1016/j.advengsoft.2012.02.003

Collins, W. & Redden, L. (2022). Assessing industry estimating software utilization practices to improve construction education. *In Proceedings of the 58th Annual Associated Schools of Construction International Conference*, *EPiC Series in Built Environment*, 3, 552-559. https://doi.org/10.29007/pp26

Gholizadeh, P., Esmaeili, B., & Goodrum, P. (2018). Diffusion of Building Information Modeling (BIM) functions in the construction industry. *Journal of Management in Engineering*, 34(2). https://doi.org/10.1061/(ASCE)ME.1943-5479.0000589

Igwe, U.S., Mohamed, S.F., & Azwarie, M.B.M.D. (2019). Recent Technologies in Construction; A Novel Search for Total Cost Management of Construction Projects. *In the Proceedings of the Sustainable and Integrated Engineering International Conference 2019*. 8-9 December 2019. Putrajaya, Malaysia. doi:10.1088/1757-899X/884/1/012041

JB Knowledge (2020). The 9th Annual Construction Technology Report. Found at www.jbknowledge.com/report

Karan, E. P., & Irizarry, J. (2015). Extending BIM interoperability to preconstruction operations using geospatial analyses and semantic web services. *Automation in Construction*, 53(1), 1-12. https://doi.org/10.1016/j.autcon.2015.02.012

Liu, M., Rasdorf, W., Hummer, J., Hollar, D., & Parikh, S. (2012). Preliminary engineering cost estimation strategy assessment for roadway projects. *Journal of Management in Engineering*, 29(2), 150–157. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000137

Lu, J., Liu, Z. H., Xu, P., & Zhang, C. (2016). *UDBMS: Road to Unification for Multi-model Data Management*. http://arxiv.org/abs/1612.08050

Martínez-Rojas, M., Marín, N., & Vila, M. (2015). The role of information technologies to address data handling in construction project management. *Journal of Computing in Civil Engineering*, 30(4). https://doi.org/10.1061/(ASCE)CP.1943-5487.0000538

Pellicer, E., Correa, C.L., Yepes, V., & Alarcón, L.F. (2012). Organizational improvement through standardization of the innovation process in construction firms. *Engineering Management Journal*, 24(2), 40-53. https://doi.org/10.1080/10429247.2012.11431935

Philip Chen, C. L., & Zhang, C. Y. (2014). Data-intensive applications, challenges, techniques and technologies: A survey on Big Data. *Information Sciences*, 275, 314–347. https://doi.org/10.1016/j.ins.2014.01.015

Smith, P. (2014). BIM & the 5D Project Cost Manager. *In the Proceedings of the 27th IPMA World Congress*, 119, 475 – 484. https://doi.org/10.1016/j.sbspro.2014.03.053

AI for Improving Construction Safety: A Systematic Literature Review

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Artificial intelligence (AI) has been adopted and applied in many fields and has now become one of the emerging technologies in the automation of the construction industry, which has gained a lot of attention from researchers in recent years. Much research work has been done on applying AI to improve construction safety. However, the current research work is focused on improving safety in separate individual construction tasks and the developed models lack real-world applications. Therefore, a systematic literature review has been conducted on the use of AI including machine learning and deep learning in improving safety in construction practice. After the review of the existing literature, the current applications and practices of AI are identified and classified. This will help in developing a new generalized framework that focuses on the entire construction process for improving safety. The limitations and the potential improvements in the existing AI techniques have been identified which will benefit future studies.

Key Words: Artificial intelligence (AI), Machine Learning, Deep Learning, Construction Safety

Introduction

It is known that the construction industry is one of the riskiest industries with many times more worker-related fatal accidents than any other industry in the world (Zhu et al. 2021). According to a report published in 2022 by the US Bureau of Labor Statistics, for the year 2020, more than 20% of worker fatal injuries in all industries are from construction workplaces. Additionally, according to (‘A look at falls, slips, and trips in the construction industry: The Economics Daily: U.S. Bureau of Labor Statistics), the number of worker’s non-fatal injuries at the workplace in the construction industry is 9.7% more than the average number in all industries. Obviously, the rate of safety improvement in the construction industry is not comparable to other industries. Therefore, revolutionary ideas are needed for improving construction safety. However, such ideas usually require a thorough analysis of existing safety performance data. With the advancement in information technology in recent years, a large amount of data can be gathered but still requires manual processing and parsing to extract useful information which is time-consuming and inefficient with many errors.

On the other hand, Artificial intelligence (AI), including machine learning and deep learning, has been rapidly developed and has been successfully used in many fields. It has been proven as an effective data mining tool to deal with a large amount of data. AI can benefit the construction industry by learning trends from previous data, minimizing human errors, and making fast decisions. Its applications in the construction industry have also significantly increased in a short period of time (Vickranth, Bommareddy, and Premalatha 2019), many of which focused on the improvement of construction safety. However, the current research work is focused on improving safety in separate individual construction tasks and the developed models lack real-world applications. Therefore, there exists a need to systematically review and analyze existing AI knowledge and applications in improving safety in construction practice and later develop possible recommendations for future research work.

The systematic literature review is a methodical procedure in research for collecting, identifying, and analyzing the existing/available literature that includes books, peer-reviewed articles, conference proceedings, etc. on a certain topic (Carrera-Rivera et al. 2022; Pati and Lorusso 2017). The main purpose of conducting a systematic literature review is to update its reader with the latest/current knowledge about a topic (B KitchenhamThe maintchenham, & Charters, 2007) and to analyze and review critical points of existing literature to suggest further research questions about a topic (Kitchenham et al. 2009). This paper reports a systematic literature review and identifies, analyzes, and classifies existing research progress on AI approaches that are focused on improving safety in construction practice. This will help in developing a new generalized framework that focuses on the entire construction process for improving safety. The limitations and improvements in the existing frameworks have also been discussed.

Methodology

The methodology used for this paper contains several steps. First, a preliminary literature review was done in an efficient manner to identify the research aim and to draw out the research questions. The question identified were:

1) How to classify improvement in safety in construction practice by using AI including machine and deep learning? and
2) What improvements can be done to existing frameworks?

Second, these questions were further investigated through a systematic literature review. The first question was addressed by collecting and reporting previous research work in tabulated form, with suggested classification. To address the second question an in-depth analysis was done on the limitations and shortcomings of existing identified research work. During the literature search, Scopus was used as the main database, which contains a vast number of peer-reviewed quality articles. To reach a broad category of information, the word "safety" was not used in the first round of searches. Instead, the keywords used were "machine learning in construction" and "deep learning in construction". Then, multiple refinements were done with a linkage to "safety" on the batch of articles shown by the search engine after using the above-stated keywords separately based on relevance, subject area, document type, and/or source type. Also, considering AI is emerging technology for construction safety, the selection of articles was from publications between 2018 to 2022. Further, articles were evaluated by analyzing their title and abstracts for final inclusion and/or exclusion. Then, the selected articles were thoroughly reviewed, and the data collected is presented in tabulated form, and went through a content classification process to reach a structured classification. As presented (in Figure 1) shows the research methodology of this study. This methodical process of selection resulted in 79 articles from various journals published between the above-stated duration/years. Conference papers were not considered for this review. Table 1 shows the breakdown of selected papers.

Table 1. Breakdown of Selected Papers.

Journal/Conference Papers	Count
Journal Papers	79
Conference Papers	0

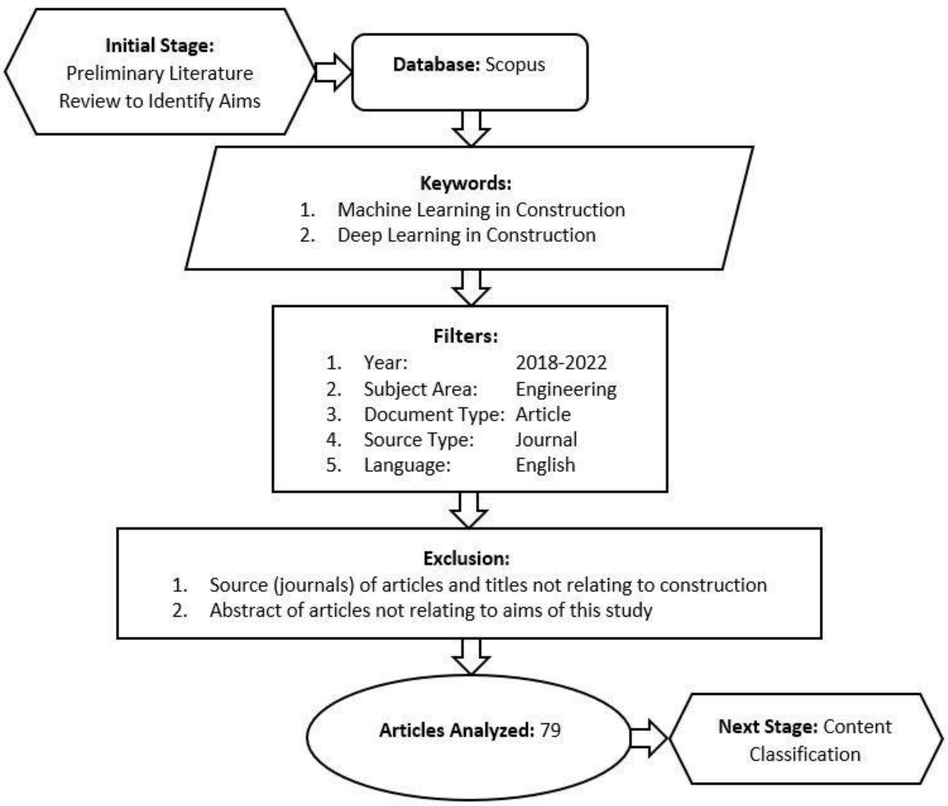

Figure 1. Research Framework

Identified AI Approaches

The three terms i.e., AI, machine learning, and deep learning are usually used interchangeably but there is a difference among them. AI refers to machines behaving intelligently like a human. Machine learning is a subset of AI where machines learn and predict using various algorithms after being trained with the previously available data. Deep learning is a subset of machine learning where machines train themselves using various neural networks and a large amount of data (Khallaf and Khallaf 2021). Further, machine learning can be divided into supervised learning, unsupervised learning, and reinforcement learning. Supervised learning, in which machines learn a trend from a labeled dataset with predetermined target variable(s), and produce prediction using new inputs, can be used for regression and classification problems, while unsupervised learning uses an unlabeled dataset without predetermined target variable(s), which can be used for clustering and data reduction. Reinforcement learning, a trial-and-error-based solution to problems, is not feasible (expensive) to be used in construction work (Xu et al. 2021). The most used machine learning algorithms are summarized in Table 2-6 containing their application, dataset, performance, and how it is used to improve construction safety, while deep learning approaches are omitted due to the limitation of the paper length; however, the discussion section will cover the deep learning as well.

Table 2. Logistic Regression (LR (Logistic)) for Improving Safety in Construction.

References	Applications	Dataset	Performance	Improvements in Framework
(Tang and Golparvar-Fard 2021)	Prediction of severity level of risk of each construction worker	Previously recorded pictures and videos taken actively during construction	Accuracy-85.7% (Bricklaying) Accuracy-86.6% (Plastering)	Enhanced validation, interobserver agreement tests for annotations, use of wearable cameras
(Zhu et al. 2021)	Prediction of consequences of construction accidents	Previously recorded construction accidents investigation reports	Precision-79.8% Recall-80.3% F1-Score-80%	Larger dataset, deep learning for feature extraction
(Choi et al. 2020)	Prediction of fatal construction accidents	Previously recorded construction injuries and deaths by the authorities	AUROC-0.6326	Larger dataset
(Poh, Ubeynarayana, and Goh 2018)	Prediction of occurrence and severity level of construction accidents	Safety monthly inspection records and accidents during construction projects by a construction firm over the years	Accuracy-59% Weighted-Kappa Statistics-0.46 Recall (Major Accident)-62%	Larger dataset with many construction firms for generalization, construction health be added with accidents

Table 3. Random Forest (RF) for Improving Safety in Construction.

References	Applications	Dataset	Performance	Improvements in Framework
(Duan et al. 2022)	Prediction of risk events in construction workers material handling	Data acquired with accelerometer and gyroscope in smartphones on wrist of five volunteer workers	Accuracy-76.71% (anterior) Accuracy-80.13% (shoulder)	Model validation in real-world scenario, devices attached to other body parts as well
(Koc, Ekmekcioğlu, and Gurgun 2021)	Prediction of construction worker's post-accident permanent disability status	Previously recorded construction accidents by the authorities	Precision-97.18% Accuracy-81.61% F1-Score-88.07% AUROC-80.94%	Larger dataset with pre-accident features as well, use of proactive data
(Zhu et al. 2021)	Prediction of consequences of construction accidents	Previously recorded construction accidents investigation reports	Precision-77.5% Recall-78.9% F1-Score-77.4%	Larger dataset, deep learning for feature extraction
(Choi et al. 2020)	Prediction of fatal construction accidents	Previously recorded construction injuries and deaths by the authorities	AUROC-91.98%	Larger dataset
(Poh et al. 2018)	Prediction of occurrence and severity level of construction accidents	Safety monthly inspection records and accidents during construction projects by a construction firm over the years	Accuracy-78% Weighted-Kappa Statistics-0.70 Recall (Major Accident)-87%	Larger dataset with many construction firms for generalizability, construction health be added with accidents

Table 4. Decision Tree (DT) for Improving Safety in Construction.

References	Applications	Dataset	Performance	Improvements in Framework
(Duan, Zhou, and Tao 2022)	Prediction of risk events in construction workers material handling	Data acquired with accelerometer and gyroscope in smartphones on wrist of five volunteer workers.	Accuracy-64.51% (anterior) Accuracy-69.14% (shoulder)	Model validation in real-world scenario, devices attached to other body parts as well
(Lee et al. 2021)	Recognition and prediction of level of perceived risk by construction workers	Physiological data gathered with wristband-type biosensors from eight workers	Accuracy-70.7%	Construction hazards not perceived by worker be considered
(Abbasianjahromi and Aghakarimi 2021)	Prediction of safety performance criteria before the start of project	Identified safety performance criteria and later data on these criteria was gathered through questionnaire	Accuracy-76%	Larger dataset, safety performance criteria be enhanced
(Mahmoodzadeh et al. 2021)	Prediction of inflow of water into the during tunnel construction	Previously recorded data acquired from road tunneling projects	R^2-72.10%	Larger dataset by considering other types of tunnels be used
(Zhu et al. 2021)	Prediction of consequences of construction accidents	Previously recorded construction accidents investigation reports	Precision-77.2% Recall-78.2% F1-Score-77.5%	Larger dataset, deep learning for feature extraction
(Choi et al. 2020)	Prediction of fatal construction accidents	Previously recorded construction injuries and deaths by the authorities	AUROC-63.16%	Larger dataset
(Poh et al. 2018)	Prediction of occurrence and severity level of construction accidents	Safety monthly inspection records and accidents during construction projects by a construction firm over the years	Accuracy-71% Weighted-Kappa Statistics-0.61 Recall (Major Accident)-81%	Larger dataset with many construction firms for generalization, construction health be added with accidents

Table 5. K Nearest Neighbor (KNN) for Improving Safety in Construction.

References	Applications	Dataset	Performance	Improvements in Framework
(Lee et al. 2021)	Recognition and prediction of level of perceived risk by construction workers	Physiological data gathered with wristband-type biosensors	Accuracy-78.8%	Construction hazards not perceived by worker be considered
(Abbasianjahromi and Aghakarimi 2021)	Prediction of safety performance criteria before the start of project	Identified safety performance criteria and later data on these criteria was gathered through questionnaire	Not Available	Larger dataset, safety performance criteria be enhanced
(Mahmoodzadeh et al. 2021)	Prediction of inflow of water into the during tunnel construction	Previously recorded data acquired from road tunneling projects	R^2-76.65%	Larger dataset by considering other types of tunnels be used
(Zhu et al. 2021)	Prediction of consequences of construction accidents	Previously recorded construction accidents investigation reports	Precision-76% Recall-77.6% F1-Score-75.9%	Larger dataset, deep learning for feature extraction
(Poh et al. 2018)	Prediction of occurrence and severity level of construction accidents	Safety monthly inspection records and accidents during construction projects	Accuracy-73% Weighted-Kappa Statistics-0.62 Recall (Major Accident)-77%	Larger dataset with many construction firms for generalizability, construction health be added with accidents

Table 6. Support Vector Machine (SVM) for Improving Safety in Construction.

References	Applications	Dataset	Performance	Improvements in Framework
(Duan et al. 2022)	Prediction of risk events in construction workers material handling	Data acquired with accelerometer and gyroscope in smartphones on wrist	Accuracy-74.89% (anterior) Accuracy-78.17% (shoulder)	Model validation in real-world scenario, devices attached to other body parts as well
(Fitzsimmons et al. 2022)	Prediction of time-risk on construction projects	Construction scheduled tasks gathered from projects over the years	Accuracy>54.4% than a Monte Carlo Simulation	Larger dataset
(Lee et al. 2021)	Recognition and prediction of level of perceived risk by construction workers	Physiological data gathered with wristband-type biosensors from eight workers	Accuracy-81.2%	Construction hazards not perceived by worker be considered
(Zhu et al. 2021)	Prediction of consequences of construction accidents	Previously recorded construction accidents investigation reports	Precision-81% Recall-78.7% F1-Score-74%	Larger dataset, deep learning for feature extraction
(Gong et al. 2020)	Evaluation of safety risk for constructing deep foundation	Previously recorded deep foundation construction safety risk reports	Accuracy-90.57%	Automated method for safety risk evaluations
(Sakhakarmi, Park, and Cho 2019)	Prediction of safety conditions to monitor the scaffolding system	Previously recorded strain data sets from scaffolding columns	Accuracy-39.13% to 82.35%	Include more local failures, automatically identification of failures
(Poh et al. 2018)	Prediction of occurrence and severity level of construction accidents	Safety monthly inspection records and accidents during construction projects by a construction firm over the years	Accuracy-44% Weighted-Kappa Statistics-0.22 Recall (Major Accident)-33%	Larger dataset with many construction firms for generalizability, construction health be added with accidents

A total of 12 main AI techniques have been identified as: (1) Logistic Regression (LR), (2) Decision Tree (DT), (3) Random Forest(RF), (4) Naïve Bayes (NB), (5) K Nearest Neighbor (KNN), (6) Support Vector Machine (SVM), (7) Gaussian Process Regression (GPR), (8) Boosting Ensembles (BE), including Adaptive Boosting (AdaBoost), and Extreme Gradient Boosting (XGBoost), (9) Artificial Neural Network (ANN), (10) Convolutional Neural Network (CNN), (11) Deep Neural Network (DNN), and (12) Recurrent Neural Network (RNN), among which (1)-(8) are machine learning algorithms and (9)-(12) are deep learning. Obviously, supervised machine learning is the most widely used learning for construction safety improvement.

Discussion

Most of the work on specific topics in improving safety in construction was done with both machine learning and deep learning techniques. Table 7 summarizes the identified AI practice in construction safety, which has classified into five sub-fields: 1) Worker Risks, 2) Construction Accidents, 3) Workers PPE, 4) Construction Machinery, and 5) Site Safety. The improvement of safety in construction was done with machine learning techniques that include LR (Logistic), DT, RF, KNN, SVM, AdaBoost, and XGBoost while the deep learning methods were ANN, CNN, DNN and RNN including their variations. The application of AI to improve safety in construction practice is still a new direction and has been making exceptional progress, but there are constraints of AI technique for specific issues limiting the full potential of AI. It has been noted that the single biggest limitation is the limited amount of construction data available for training the model. The performance of machine learning and deep learning prediction models is as good as the data used for their training. From the review of the identified literature, it is observed that previous data was either limited to a few features or collected manually, and with this limited scope, the generalizability of the models has not been achieved. Broad-based automated data collection methods are to be considered covering all aspects of the problem collected not from one region but instead, the region for data collection should be broad. There is still a need to achieve the full integration of AI into the construction practice.

Table 7. Identified AI Approaches for Improving Safety in Construction.

References	AI Approach	Topics
(Duan et al. 2022)	DT, RF, SVM, ANN	Worker Risk Events
(Fitzsimmons et al. 2022)	SVM	Time-Risk on Projects
(Koc, Ekmekcioğlu, and Gurgun 2022)	ANN	Construction Accidents
(Xiao et al. 2022)	Mask R-CNN	Off-Site Worker Tracking
(Pan et al. 2022)	CNN+word2vec	Equipment Security Data
(Arashpour et al. 2022)	DNN	Monitoring Heavy Machinery
(Pan and Zhang 2022)	DNN + GDO	Risk in Tunnel Construction
(Antwi-Afari et al. 2022)	LSTM+BiLSTM+GRU	Awkward Worker Posture
(Koc et al. 2021)	RF, AdaBoost, GBM, XGBoost	Worker Post-Accident Disability
(Tang and Golparvar-Fard 2021)	LR (Logistic)	Worker Risk Severity Level
(Harichandran, Raphael, and Mukherjee 2021)	ANN	Auto Construction Operations
(Zhu et al. 2021)	LR (Logistic), DT, RF, NB, KNN, SVM, ANN	Construction Accidents Consequences
(Lee et al. 2021)	DT, KNN, SVM	Worker Perceived Risk
(Abbasianjahromi and Aghakarimi 2021)	DT, KNN	Safety Performance Criteria
(Mahmoodzadeh et al. 2021)	DT, KNN, GPR	Water Inflow in Tunnel Construction
(Wang, Antos, and Triveno 2021)	Mask R-CNN	Masonry Building Prone to Earthquake
(B. Kim et al. 2021)	DenseNet	Buildings Steel Frames
(K. Kim, Kim, and Shchur 2021)	CNN	Site Monitoring for Unsafe Activities
(Chen and Demachi 2021)	YOLOv3	Monitoring PPE at Site
(Son and Kim 2021)	YOLOv4	Worker & Machinery Tracking
(Kim and Cho 2021)	LSTM	Worker Motion & Activity
(Luo et al. 2021)	GRU	Detecting Machine Poses
(Choi et al. 2020)	LR (Logistic), DT, RF, AdaBoost	Fatal Construction Accidents
(Gong et al. 2020)	SVM, AdaBoost	Safety Risk for Deep Foundations
(Guo, Xu, and Li 2020)	OAF-SSD	Dense Vehicles Identification
(Zhong et al. 2020)	CNN	Construction Accident Text Evaluation
(Nath, Behzadan, and Paal 2020)	YOLOv3	PPE at Site
(Sakhakarmi et al. 2019)	SVM	Safety for Scaffolding
(Son et al. 2019)	ResNet152+R-CNN	Identify Workers with their Poses
(Kouzehgar et al. 2019)	CNN	Cracked Glass Detection with Robot
(Poh et al. 2018)	LR (Logistic), DT, RF, KNN, SVM	Construction Accidents
(Kolar, Chen, and Luo 2018)	VGG-16	Safety Guardrails at Site
(Fang et al. 2018)	Faster R-CNN	Worker Hardhat Detection

Conclusion

A systematic literature review has been conducted to identify AI techniques including machine learning and deep learning techniques that have been used for the improvement of construction practice by focusing on the safety aspect. It was concluded that most of the research work related to AI in construction has been done on the improvement of the safety aspect of construction, while the other major fields are productivity and cost. For safety, however, the focus has been on the improvement of specific or individualized safety-related tasks and not considering the overall safety of the construction practice as a whole. Considering this, a structured classification has been done in which sub-fields have been identified (1-Worker Risks, 2-Construction Accidents, 3-Workers PPE, 4-Construction Machinery, and 5-Site Safety) for the improvement of the overall safety of a project and also identifies specific AI techniques that should be used for improving safety. This here also provides a sense of direction for future work in which an AI-based comprehensive framework should be developed that covers all safety aspects and which should help improve the overall safety of construction projects. This review also identified the limitations and shortcomings of the existing frameworks for the contribution of AI techniques in improving safety in construction practice. It was concluded that with many specific limitations, the dataset used for training the AI techniques is small due to the lack of availability of the construction data which is stopping the generalizability of the developed models. A bigger and broader dataset is needed to be developed to use AI in the real-world.

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References

Abbasianjahromi, H., and M. Aghakarimi. 2021. 'Safety Performance Prediction and Modification Strategies for Construction Projects via Machine Learning Techniques'. *Engineering, Construction and Architectural Management*. doi: 10.1108/ECAM-04-2021-0303.

Antwi-Afari, M. F., Y. Qarout, R. Herzallah, S. Anwer, W. Umer, Y. Zhang, and P. Manu. 2022. 'Deep Learning-Based Networks for Automated Recognition and Classification of Awkward Working Postures in Construction Using Wearable Insole Sensor Data'. *Automation in Construction* 136. doi: 10.1016/j.autcon.2022.104181.

Arashpour, M., V. Kamat, A. Heidarpour, M. R. Hosseini, and P. Gill. 2022. 'Computer Vision for Anatomical Analysis of Equipment in Civil Infrastructure Projects: Theorizing the Development of Regression-Based Deep Neural Networks'. *Automation in Construction* 137. doi: 10.1016/j.autcon.2022.104193.

Carrera-Rivera, Angela, William Ochoa, Felix Larrinaga, and Ganix Lasa. 2022. 'How-to Conduct a Systematic Literature Review: A Quick Guide for Computer Science Research'. *MethodsX* 9:101895. doi: 10.1016/J.MEX.2022.101895.

Chen, S., and K. Demachi. 2021. 'Towards On-Site Hazards Identification of Improper Use of Personal Protective Equipment Using Deep Learning-Based Geometric Relationships and Hierarchical Scene Graph'. *Automation in Construction* 125. doi: 10.1016/j.autcon.2021.103619.

Choi, J., B. Gu, S. Chin, and J. S. Lee. 2020. 'Machine Learning Predictive Model Based on National Data for Fatal Accidents of Construction Workers'. *Automation in Construction* 110. doi: 10.1016/j.autcon.2019.102974.

Duan, P., J. Zhou, and S. Tao. 2022. 'Risk Events Recognition Using Smartphone and Machine Learning in Construction Workers' Material Handling Tasks'. *Engineering, Construction and Architectural Management*. doi: 10.1108/ECAM-10-2021-0937.

Fang, Q., H. Li, X. Luo, L. Ding, H. Luo, T. M. Rose, and W. An. 2018. 'Detecting Non-Hardhat-Use by a Deep Learning Method from Far-Field Surveillance Videos'. *Automation in Construction* 85:1–9. doi: 10.1016/j.autcon.2017.09.018.

Fitzsimmons, J. P., R. Lu, Y. Hong, and I. Brilakis. 2022. 'CONSTRUCTION SCHEDULE RISK ANALYSIS - A HYBRID MACHINE LEARNING APPROACH'. *Journal of Information Technology in Construction* 27:70–93. doi: 10.36680/j.itcon.2022.004.

Gong, P., H. Guo, Y. Huang, and S. Guo. 2020. 'Safety Risk Evaluations of Deep Foundation Construction Schemes Based on Imbalanced Data Sets'. *Journal of Civil Engineering and Management* 26(4):380–95. doi: 10.3846/jcem.2020.12321.

Guo, Y., Y. Xu, and S. Li. 2020. 'Dense Construction Vehicle Detection Based on Orientation-Aware Feature Fusion Convolutional Neural Network'. *Automation in Construction* 112. doi: 10.1016/j.autcon.2020.103124.

Harichandran, A., B. Raphael, and A. Mukherjee. 2021. 'A Hierarchical Machine Learning Framework for the Identification of Automated Construction Operations'. *Journal of Information Technology in Construction* 26:591–623. doi: 10.36680/j.itcon.2021.031.

Khallaf, R., and M. Khallaf. 2021. 'Classification and Analysis of Deep Learning Applications in Construction: A Systematic Literature Review'. *Automation in Construction* 129. doi: 10.1016/j.autcon.2021.103760.

Kim, B., N. Yuvaraj, H. W. Park, K. R. S. Preethaa, R. A. Pandian, and D. E. Lee. 2021. 'Investigation of Steel Frame Damage Based on Computer Vision and Deep Learning'. *Automation in Construction* 132. doi: 10.1016/j.autcon.2021.103941.

Kim, K., and Y. K. Cho. 2021. 'Automatic Recognition of Workers' Motions in Highway Construction by Using Motion Sensors and Long Short-Term Memory Networks'. *Journal of Construction Engineering and Management* 147(3). doi: 10.1061/(ASCE)CO.1943-7862.0002001.

Kim, K., S. Kim, and D. Shchur. 2021. 'A UAS-Based Work Zone Safety Monitoring System by Integrating Internal Traffic Control Plan (ITCP) and Automated Object Detection in Game Engine Environment'. *Automation in Construction* 128. doi: 10.1016/j.autcon.2021.103736.

Kitchenham, Barbara, O. Pearl Brereton, David Budgen, Mark Turner, John Bailey, and Stephen Linkman. 2009. 'Systematic Literature Reviews in Software Engineering – A Systematic Literature Review'. *Information and Software Technology* 51(1):7–15. doi: 10.1016/J.INFSOF.2008.09.009.

Kitchenham, B., B. Kitchenham, and S. Charters. 2007. *Guidelines for Performing Systematic Literature Reviews in Software Engineering*.

Koc, K., Ö. Ekmekcioğlu, and A. P. Gurgun. 2021. 'Integrating Feature Engineering, Genetic Algorithm and Tree-Based Machine Learning Methods to Predict the Post-Accident Disability Status of Construction Workers'. *Automation in Construction* 131. doi: 10.1016/j.autcon.2021.103896.

Koc, K., Ö. Ekmekcioğlu, and A. P. Gurgun. 2022. 'Accident Prediction in Construction Using Hybrid Wavelet-Machine Learning'. *Automation in Construction* 133. doi: 10.1016/j.autcon.2021.103987.

Kolar, Z., H. Chen, and X. Luo. 2018. 'Transfer Learning and Deep Convolutional Neural Networks for Safety Guardrail Detection in 2D Images'. *Automation in Construction* 89:58–70. doi: 10.1016/j.autcon.2018.01.003.

Kouzehgar, M., Y. Krishnasamy Tamilselvam, M. Vega Heredia, and M. Rajesh Elara. 2019. 'Self-Reconfigurable Façade-Cleaning Robot Equipped with Deep-Learning-Based Crack Detection Based on Convolutional Neural Networks'. *Automation in Construction* 108. doi: 10.1016/j.autcon.2019.102959.

Lee, B. G., B. Choi, H. Jebelli, and S. Lee. 2021. 'Assessment of Construction Workers' Perceived Risk Using Physiological Data from Wearable Sensors: A Machine Learning Approach'. *Journal of Building Engineering* 42. doi: 10.1016/j.jobe.2021.102824.

Luo, H., M. Wang, P. K. Y. Wong, J. Tang, and J. C. P. Cheng. 2021. 'Construction Machine Pose Prediction Considering Historical Motions and Activity Attributes Using Gated Recurrent Unit (GRU)'. *Automation in Construction* 121. doi: 10.1016/j.autcon.2020.103444.

Mahmoodzadeh, A., M. Mohammadi, K. M Gharrib Noori, M. Khishe, H. Hashim Ibrahim, H. Farid Hama Ali, and S. Nariman Abdulhamid. 2021. 'Presenting the Best Prediction Model of Water Inflow into Drill and Blast Tunnels among Several Machine Learning Techniques'. *Automation in Construction* 127. doi: 10.1016/j.autcon.2021.103719.

Nath, N. D., A. H. Behzadan, and S. G. Paal. 2020. 'Deep Learning for Site Safety: Real-Time Detection of Personal Protective Equipment'. *Automation in Construction* 112. doi: 10.1016/j.autcon.2020.103085.

Pan, X., B. Zhong, D. Sheng, X. Yuan, and Y. Wang. 2022. 'Blockchain and Deep Learning Technologies for Construction Equipment Security Information Management'. *Automation in Construction* 136. doi: 10.1016/j.autcon.2022.104186.

Pan, Y., and L. Zhang. 2022. 'Mitigating Tunnel-Induced Damages Using Deep Neural Networks'. *Automation in Construction* 138. doi: 10.1016/j.autcon.2022.104219.

Pati, Debajyoti, and Lesa N. Lorusso. 2017. 'How to Write a Systematic Review of the Literature'. *HERD: Health Environments Research & Design Journal* 11(1):15–30. doi: 10.1177/1937586717747384.

Poh, C. Q. X., C. U. Ubeynarayana, and Y. M. Goh. 2018. 'Safety Leading Indicators for Construction Sites: A Machine Learning Approach'. *Automation in Construction* 93:375–86. doi: 10.1016/j.autcon.2018.03.022.

Sakhakarmi, S., J. Park, and C. Cho. 2019. 'Enhanced Machine Learning Classification Accuracy for Scaffolding Safety Using Increased Features'. *Journal of Construction Engineering and Management* 145(2). doi: 10.1061/(ASCE)CO.1943-7862.0001601.

Son, H., H. Choi, H. Seong, and C. Kim. 2019. 'Detection of Construction Workers under Varying Poses and Changing Background in Image Sequences via Very Deep Residual Networks'. *Automation in Construction* 99:27–38. doi: 10.1016/j.autcon.2018.11.033.

Son, H., and C. Kim. 2021. 'Integrated Worker Detection and Tracking for the Safe Operation of Construction Machinery'. *Automation in Construction* 126. doi: 10.1016/j.autcon.2021.103670.

Tang, S., and M. Golparvar-Fard. 2021. 'Machine Learning-Based Risk Analysis for Construction Worker Safety from Ubiquitous Site Photos and Videos'. *Journal of Computing in Civil Engineering* 35(6). doi: 10.1061/(ASCE)CP.1943-5487.0000979.

Vickranth, V., S. S. R. Bommareddy, and V. Premalatha. 2019. 'Application of Lean Techniques, Enterprise Resource Planning and Artificial Intelligence in Construction Project Management'. *International Journal of Recent Technology and Engineering* 7(6C2):147–53.

Wang, C., S. E. Antos, and L. M. Triveno. 2021. 'Automatic Detection of Unreinforced Masonry Buildings from Street View Images Using Deep Learning-Based Image Segmentation'. *Automation in Construction* 132. doi: 10.1016/j.autcon.2021.103968.

Xiao, B., H. Xiao, J. Wang, and Y. Chen. 2022. 'Vision-Based Method for Tracking Workers by Integrating Deep Learning Instance Segmentation in off-Site Construction'. *Automation in Construction* 136. doi: 10.1016/j.autcon.2022.104148.

Xu, Y., Y. Zhou, P. Sekula, and L. Ding. 2021. 'Machine Learning in Construction: From Shallow to Deep Learning'. *Developments in the Built Environment* 6. doi: 10.1016/j.dibe.2021.100045.

Zhong, B., X. Pan, P. E. D. Love, L. Ding, and W. Fang. 2020. 'Deep Learning and Network Analysis: Classifying and Visualizing Accident Narratives in Construction'. *Automation in Construction* 113. doi: 10.1016/j.autcon.2020.103089.

Zhu, R., X. Hu, J. Hou, and X. Li. 2021. 'Application of Machine Learning Techniques for Predicting the Consequences of Construction Accidents in China'. *Process Safety and Environmental Protection* 145:293–302. doi: 10.1016/j.psep.2020.08.006.

Identifying Important Electrical Knowledge for Construction Management Students: An Industry Perspective

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Advances in construction technology and practices reflect the need for a curriculum that addresses an increasingly complex construction environment. Most higher education learning institutions that offer a construction management program subscribe to the American Council for Construction Education (ACCE) accreditation requirements. While these guidelines for accreditation provide a degree of uniformity among institutions, they typically cover only essential core skills and do not identify every element that should be taught over an entire curriculum. This paper describes the results of an industry survey to gain feedback on what they desired from our graduates in the area of electrical knowledge. An important conclusion from this study is that skills are ranked differently by electrical contractors and construction managers or general contractors. The survey results are presented with a limited analysis of the data and observation on the findings.

Key Words: Construction Curriculum, Electrical Knowledge, Construction Education, Electrical Survey

Introduction

Historically construction management programs have risen from a variety of other disciplines. There is a wide variety of degrees and courses of study that can ultimately land a college graduate in a construction management position within the construction industry. Aspects of early civil engineering programs lend themselves to the area of construction education. Throughout the 1900's there was a growth of knowledge that somewhat formalized specialty tracts of civil engineering. In the first half of the twentieth century there were a few civil engineering programs that showed a specialization in construction engineering. As this specialization gained popularity there was more curriculum than could adequately be incorporated in the civil engineering degree. After World War II there was a gradual need for the formation of construction specialty degree undergraduate programs (Abudayyeh, Russell, Johnston, & Rowings, 2000). This specialty degree was civil engineering at its roots but incorporated aspects of structural engineering. Initially construction engineering education was civil engineering with a focus on the entire life cycle of a physical facility, which includes conception, design, procurement, construction, operation, and maintenance (Householder & Rutland, 1990). The construction boom following World War II created a demand for more construction engineers. In response to this boom there was an establishment of a Bachelor of Science (BS) degree in construction. The BS in construction was not engineering accredited but incorporated many engineering courses as its foundation.

The construction industry recognized the need for educational programs that teach the "business of managing the construction process" (Badger, Robson, & others, 2000). Construction management education's mission was to create college educated constructors. A number of universities currently offer non-engineering BS degrees in construction management, building science, building construction, and industrial technology. The American Council for Construction Education (ACCE) accredits these degrees. There are currently 62 baccalaureate construction programs accredited by the ACCE. These curricula are a combination of engineering technology, construction techniques, business and management. There is a larger emphasis placed on management and business and less on math, science, engineering and other technical knowledge in many of today's construction management (CM) programs (Abudayyeh et al., 2000).

The skills a construction manager brings to a company or project team play a major role in the success of the projects. As the demand for higher performance throughout the life cycle of new buildings increases, owners call for more complex projects insisting teams complete them “better, faster, cheaper, and always safer” (Tatum, 2005). With trends like these, industry is looking for graduates whom are able to manage the construction process and are job ready as they leave their CM programs. Providing a construction education that parallels the changing expectations of the construction industry is the only way to achieve this. With ACCE program accreditation there is some uniformity, however a wide variety of degree titles and locations of programs within different departments at different universities exists. CM programs must constantly be adjusted and enhanced to address the education needs of industry and hence the students (Farooqui & Ahmed, 2009). There is no absolute way to do this without research into what the industry’s perception is on the current state of construction management education.

To gain the knowledge necessary to properly adjust the spotlight of construction education curriculums is a difficult process. There is no easy or quick way of determining what is necessary to most effectively prepare the building professionals of tomorrow for their career in the construction industry. The rapid development of new technologies and innovations combined with new delivery methods and construction practices have created a demand for graduates with a strong foundation of technical knowledge to effectively manage the ever changing construction process. Within this foundation of technical knowledge there needs to be placed emphasis on electrical skills that lend themselves to a majority of construction activities.

The majority of graduates from a CM program begin employment with either a construction management or general contracting (GC) firm. Placement opportunities with specialty contractors do occur however, as the general knowledge offered by the construction management program’s in estimating, scheduling, contracts, materials, and management skills make graduates attractive to specialty contractors. In developing a course in the electrical area it is desirable to teach topics that not only benefit the GC/CM environment, but also the electrical contractor (EC).Within the past 3 years, curriculum reviews have been conducted to ensure compliance with ACCE requirements and to also determine if the needs of supporting industry partners were being met. One result of the review concluded that industry would like to see graduates have a better understanding of electrical and mechanical subjects. In response to this, the curriculum was expanded from one combined three hour mechanical/electrical course to two separate three hour courses, each with a lab component. Once the decision was made to change the course content, the next logical question was to ask just what should be taught in these courses. To answer this question a survey was developed and distributed to various members of industry. Since only a limited number of curriculum hours can be devoted to the electrical subject, it became clear that a research tool needed to be structured so that topics could eventually be ordered in a most desirable to least desirable hierarchy. An added advantage to obtaining results that allow topics to be ranked makes the results useful for other institutions that may devote additional hours to the subject with multiple courses or specialty tracts. The results of this research led to the development of an extensive survey which was delivered to industry professionals, both GC/CM companies as well as electrical contractors, to answer the question, what topics should be covered in an electrical course as part of a construction management degree.

Objectives

The construction industry continues to change with new technologies. This study investigates the opinions of industry partners to identify what areas of electrical subjects are important for perspective employees to be aware of when graduating from a construction management / building science program. The answers to questions posed in the surveys supplemented by one on one meetings with industry professionals can provide useful information when reviewing the content of electrical course material being taught. The objective of this research is to provide information useful to making systematic and informed refinements to the electrical classes being taught.

Methodology

The research methodology consisted of the following steps:

1. Development of a questionnaire based survey used to elicit information about the desired skills construction management students should have upon graduation in the area of electrical systems.
2. Conducting the survey through in-person as well as email and online distribution methods.
3. Conducting two 1 day workshops with industry advisory participants to review the survey results and gain further knowledge based on industry evaluation and input.
4. Analysis of the results to identify the industry desired skills in the areas of electrical knowledge.

The focus of the survey was to identify electrical skills the respondent thought would be beneficial for a graduate of a construction management program. The questions were prepared after an extensive review of current curricula being taught at Auburn including many texts typically used in the electrical classes within construction management programs. The National Electrical Code® was also used to determine appropriate skill set questions.

Two initial questions were asked to gather information about the respondent's type of company - General Contractor (GC), Construction Management (CM), Electrical Contractor (EC), or Other, and to determine the type of work the respondent is most involved with (e.g. healthcare, educational, office, retail, hotel/apartment/ condo, industrial, or other). Fifty two questions identified specific electrical skills divided into 11 categories: 1) electrical project execution, 2) electrical utilization equipment, 3) electrical circuits, 4) general electrical requirements, 5) electrical materials, 6) emergency systems, 7) special systems, 8) lighting, 9) electrical distribution equipment, 10) building electrical systems, and 11) electrical principles. Participants were asked to rate each question using a Likert scale, with 1 being the least important and 6 being a crucial topic.

Details on how the survey was developed can be found in an ASC Proceedings Paper entitled What to Teach – Electrical Survey Industry Response (Tatum and Sutherland, 2014)

The survey was distributed to electrical industry throughout the United States using Electri International and the National Electrical Contractors Association (NECA). Respondents from the general building industry in the southeastern United States were solicited using the Associated Builders and Contractors Association (ABC), and the Associated General Contractors Association (AGC).

Data and Results

To date 260 surveys have been distributed with 89% or 230 respondents completing the survey. These include 29 participants for the two workshops. Figure 1 shows the breakdown of respondents based on their company's category. Figure 2 indicates the respondent's particular area of expertise.

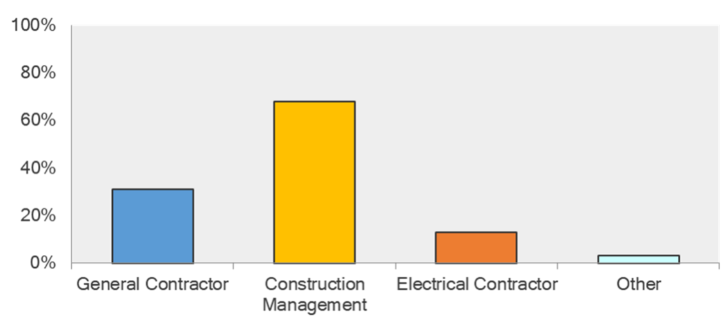

Figure 1: Survey Respondent's Company Demographics

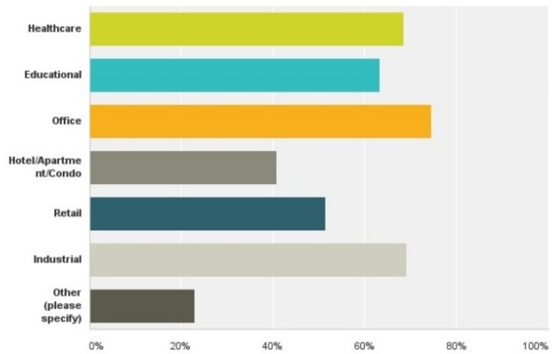

Figure 2: Survey Respondent's Area of Expertise

Data Analysis

The data collected from the survey was analyzed by using the mean level of significance for each electrical skill based on the Likert scale response. This was used to compare and rank the relative importance of the individual skills and to determine what the respondents felt were the most important skills for a construction management graduate. The overall survey results can be found in the appendix.

The first observation was to notice the overall mean level of significance of the electrical subjects as registered by the respondents. In Figure 3 it can be seen that the electrical contractors placed more overall importance on the electrical subjects than did the respondents outside the electrical contracting field. This can most likely be attributed to the electrical contractor's focus in this area. While all the questions are limited to electrical subjects, this difference in respondent's level of importance could impact the relative ranking of a given subject. For example, estimating or scheduling might receive an overall higher ranking than another subject because of the GC and CM's familiarity with this activity and its importance in their area of work. This impact would also vary according to the number of survey responses obtained from the different groups.

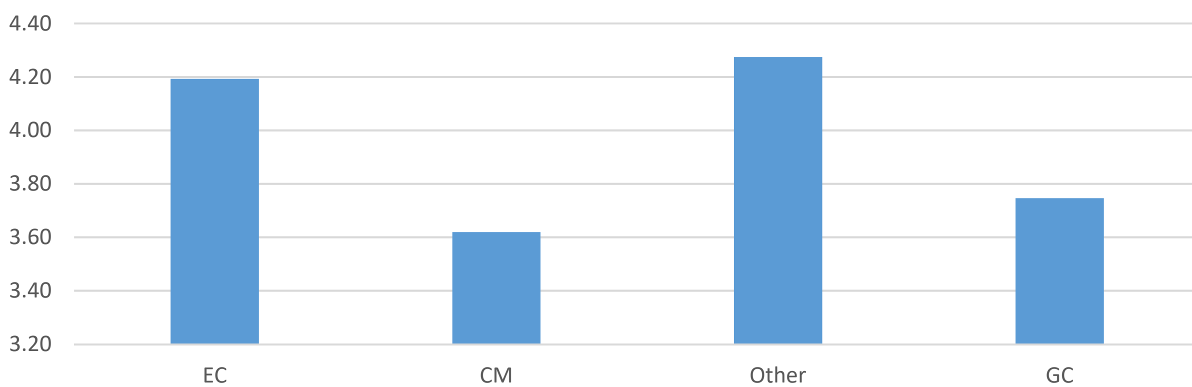

Figure 3: Overall Survey Mean Responses by Trade

Figure 4 shows the 11 categories of electrical questions. These category mean ratings were obtained by averaging the ratings of all the questions asked within that category. This allows one to find which category has the highest level of value according to the industry respondents. From the figure it can be seen that the categories with the highest mean value are: general electric requirements, electrical project execution, building electrical systems, and electrical distribution equipment.

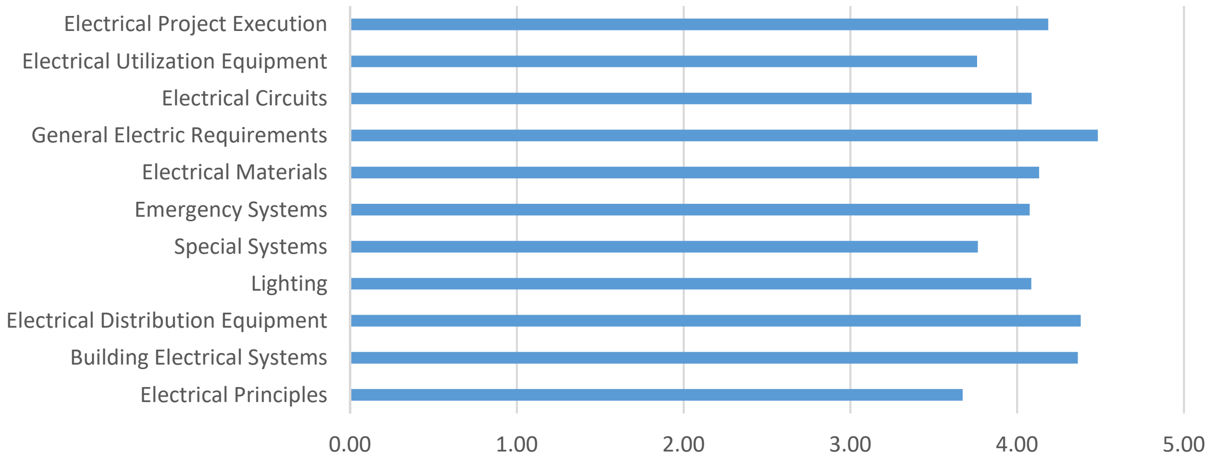

Figure 4: Average Rating for Electrical Question Categories

Within these categories are important skills for all trades encompassing areas from management skill to safety knowledge. The electrical project execution subcategory was especially rated highly by the construction management profession. This category includes skills paramount to the safety of the jobsite such as Occupational Safety and Health Administration (OSHA) requirements and compliance with the National Electrical safety code. The electrical project execution category also includes items such as the ability to understand temporary jobsite power and lighting requirements, the ability to write and review contract documents, and the ability to coordinate work with other trades. These are all skills needed to be a successful CM or GC where the responsibility to oversee the jobsite is theirs.

The appendix shows the survey responses to all individual questions. It is presented in a way that allows one to see the question, the category, and the group (EC, GC, CM or Other) responding. Each group (trade) rank is an average of all responses for that question from that group. The overall ranking at the right of the table is weighted by the number of responses obtained from each group.

The electrical contractor felt knowledge of building electrical systems was of high importance. The knowledge of how single phase and three phase systems as well as voltage differences in systems is desired of graduates. These very technical skills are required to have an understanding of why a certain system was specified within a building and how that system works. By looking at how each group answered the questions one can begin to develop an understanding of why the different trades may value different skills differently. By looking at how the trades answer the question "please rate on a scale of 1-6, Ability to read and understand control diagrams, ladder diagrams, relays, interlocks, and switches" it can be seen that the electrical contractor assigned this skill a mean value of 4.39 on a scale of 1 to 6. It is safe to say that this is a skill necessary to carry out their daily work and important to the electrical contractor's scope of work. The GC rated this with 3.2. While a GC may understand relays and interlocks, he may not know how to read the ladder diagrams. Since this is not in his immediate scope of work, it may be of lesser importance to the GC and thus received a lower level of importance than for the electrical contractor. This same process can be used to analyze any of the other skills and traits.

Conclusions

Every trade places a different amount of value or priority to electrical education within a building science curriculum. What was found was industry desires graduates who have an overall knowledge of the electrical field. Many students will end up working for a GC or CM where the ability to interact and communicate with other trades especially the electrical trade is paramount to the success of a project. The GC and CM trades would like to see a curriculum that provides students an overview of the electrical field. They would like to have the curriculum concentrate and provide a more in depth knowledge of areas such as OSHA regulations, the ability to coordinate work between trades. They also seek students who are able to read the documents, both plans as well as contract documentation. Some students will end up working for an electrical contractor where students who are proficient in understanding electrical plans and electrical equipment are desirable. The electrical contractor would like to hire students with a good understanding of the electrical field but who also have the skills taught in other areas of the building science curriculum.

Even though there are some differences in the responses among the groups, there is much agreement as to the electrical skills desired in students. These skills therefore should be the basis for the curriculum for a building science electrical course. Some of the skills found common to all groups include:

- The ability to provide coordination with both other contractors and systems found on a job
- The ability to understand and read panel schedules
- The ability to understand and read single line diagrams
- The ability to understand basic electrical plan symbols
- The knowledge of OSHA requirements
- A knowledge of electrical distribution systems
- A understanding of major electrical equipment

There are numerous other statistical analysis exercises that can be done to extract useful information from this data. Due to the limitation of space for a proceedings publication, this paper only deals with the presentation of the data itself. Using the results from this survey, one can not only determine what subjects should be taught but also how much time should be spent in specific areas. Since individual programs allot different course hours to be devoted to electrical subjects, the relative time spent on individual subjects is an important result of the analysis.

A subsequent paper is planned where further analysis will be performed to develop an electrical course outline suitable for a construction management program. This study will define what will be taught and how much time should be dedicated to each topic. It will also define how much depth each topic will address.

References

Abudayyeh, O., Russell, J., Johnston, D., & Rowings, J. (2000). Construction Engineering and Management Undergraduate Education. *Journal of Construction Engineering and Management*, *126*(3), 169–175.

Badger, W. W., Robson, K., & others. (2000). Raising Expectations in Construction Education. *Construction Congress VI@ sBuilding Together for a Better Tomorrow in an Increasingly Complex World* (pp. 1151–1164). Retrieved from http://ascelibrary.org/doi/pdf/10.1061/40475(278)125

Farooqui, R. U., & Ahmed, S. M. (2009). Key Skills for Graduating Construction Management Students—A Comparative Study of Industry and Academic Perspectives. *Construction Research Congress*. Retrieved from http://ascelibrary.org/doi/abs/10.1061/41020(339)146

Householder, J. L., & Rutland, H. E. (1990). Who owns float? *Journal of Construction Engineering and Management*, *116*(1), 130–133.

Tatum, C. B. (2005). Building Better: Technical Support for Construction. *Journal of Construction Engineering and Management*, *131*(1), 23–32. doi:10.1061/(ASCE)0733-9364(2005)131:1(23)

Tatum, M.C., & Sutherland S. (2014). What to Teach – Electrical Survey Industry Response. *50th ASC Annual International Conference Proceedings.*

Appendix A

Survey Response Data

Rank	Question # and Descriptions	EC	CM	GC	Other	Overall Rank
1	Understanding and reading electrical single line (or riser) diagrams	5.05	4.63	4.50	5.17	4.88
2	Understanding basic electrical plan symbols	4.92	5.00	4.60	5.17	4.81
3	OSHA requirements	4.79	5.13	4.80	4.83	4.71
4	Types of major electrical equipment-switchboards, switchgear, panel boards, load centers, motor control centers, and transformers	4.75	4.25	4.50	5.00	4.63
5	Lock-out/Tag-out procedures	4.72	4.88	4.40	4.33	4.60
6	Learning typical coordination requirements with other contractors and systems	4.64	4.75	4.30	4.50	4.53
7	Electrical distribution systems- why are there different system voltages	4.62	4.50	4.20	4.71	4.51
8	Familiarity with the National Electrical Safety Code	4.71	3.63	3.90	4.67	4.50
9	How single phase and three phase systems work-what is the difference	4.57	3.78	4.90	4.57	4.46
10	Preparing an electrical bid including labor and markups	4.75	3.63	3.10	4.00	4.44
11	Ability to perform an electrical plan take-off	4.80	2.38	3.20	4.33	4.44
12	Review of typical contracts for electrical work with different delivery methods-prime contractor, sub-contractor, design build, etc.	4.55	4.63	3.80	4.83	4.43
13	Understanding and ability to read panel schedules	4.51	4.38	4.20	5.00	4.42
14	Lighting sources- fluorescent, incandescent, HID, LED, etc.	4.50	3.88	4.40	4.29	4.37
15	Electrical equipment clearances and installation requirements	4.56	4.13	3.60	4.00	4.37
16	Wiring methods-conductor cables, conductors in raceways	4.47	3.38	4.40	4.60	4.34
17	Electrical grounding and bonding requirements	4.55	3.25	3.30	4.50	4.32
18	Electrical raceway systems-conduit types, cable tray, wireways, flexible conduit, etc.	4.46	3.50	4.10	4.33	4.30
19	Circuit Breakers and Fuses- overcurrent and short circuit protection	4.44	3.25	4.10	4.83	4.30
20	Writing an electrical scope of work	4.40	4.00	4.10	4.33	4.28
21	Determining crew size and project man loading schedules	4.58	3.00	3.20	3.67	4.28
22	Calculating basic circuit sizes- finding the ampacity requirements for branch circuits and feeders	4.42	3.13	3.40	4.67	4.22
23	Acquiring pricing information from vendors and other sources	4.31	4.50	3.90	4.17	4.22
24	How electrical panels supply different voltages- 1 pole, 2 pole, & 3 pole circuit breakers	4.33	3.50	4.10	4.57	4.22
25	Generators and UPS systems	4.31	4.25	3.70	4.00	4.19
26	Ability to read and understand control diagrams-ladder diagrams, relays, interlocks and switches (limit, proximity, temperature, pressure, flow, etc.	4.39	3.00	3.20	5.00	4.19
27	Lighting control systems- dimming, automation, and energy savings	4.23	3.75	3.80	4.67	4.14
28	Understanding conductor ratings-insulation type, temperature, and ampacity	4.32	2.75	3.70	4.50	4.14
29	Arc Fault and Ground Fault equipment requirements	4.30	3.25	3.40	4.33	4.12
30	How series and parallel circuits are used in buildings- switches and load connections	4.14	4.00	4.60	4.33	4.12
31	Voltage drop in circuits and how to calculate	4.27	2.38	3.30	4.43	4.06
32	Fire Alarm systems	4.10	4.13	4.20	3.83	4.05

33	Electrical devices-receptacles, switches, disconnects, and fixtures- NEMA designations	4.13	3.25	4.00	4.50	4.03
34	Battery backup for egress/emergency lighting	4.09	4.13	3.40	3.83	3.99
35	Transformer Types-how they function	3.98	3.38	3.60	4.14	3.90
36	Temporary jobsite power and lighting	3.83	4.88	4.30	3.83	3.89
37	Methods used to make wiring connections-marking & color coding	3.90	3.88	3.40	4.33	3.85
38	Requirements and calculations for motor circuits- short circuit and overload protection for single phase and 3 phase motors	4.03	2.63	2.80	4.33	3.83
39	Lighting design-calculating lighting levels	3.92	2.75	3.60	3.86	3.80
40	Residential and commercial service calculations	3.81	2.38	3.30	4.20	3.68
41	Requirements and calculations for air conditioning circuits- nameplate ratings, minimum circuit ampacity, maximum fuse/circuit breaker size and full load amps	3.79	3.00	3.00	4.17	3.68
42	Measuring AC voltage and current-true RMS values and harmonics	3.77	3.00	3.30	3.71	3.67
43	Ability to use typical metering and test equipment	3.69	3.00	3.90	4.17	3.67
44	Communication systems-telephone and data	3.61	4.00	3.80	4.17	3.66
45	AC and DC systems-why do we use AC for buildings	3.59	3.78	3.80	4.57	3.65
46	Access control systems- (card, keypad, etc.) and intrusion detection	3.46	3.88	3.20	4.00	3.48
47	Electrical Energy Sources-solar, batteries, generators, hydro-electric, nuclear, coal, etc.	3.50	2.78	3.40	4.00	3.47
48	Intercom, Nurse Call, and other audio systems	3.32	4.25	3.10	3.33	3.36
49	Power factor in AC circuits-primarily caused by motor loads and is considered in generator sizing	3.34	2.88	2.90	3.43	3.29
50	Installing and connecting basic electrical devices and equipment- outlets, switches, fixtures, etc.	3.29	2.88	3.30	3.17	3.27
51	How to bend conduit and pull wire	3.28	2.25	2.90	3.00	3.20
52	Ability to make electrical connections- including communication cable terminations	3.22	2.75	2.90	3.33	3.19

Building Information Modeling and Value Engineering for Project Schedule and Cost Control

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Architectural, Engineering, and Construction industry personnel continuously face challenges in executing projects within budget and schedule. Scheduling and cost control are vital processes for achieving project success. A study proposed a framework for integrating building information modeling (BIM) and value engineering (VE) processes to enhance value, minimize costs, improve schedules, and ease information exchange. A case study building project was used to demonstrate how BIM and VE integration can be harmonized and validate the proposed method. The findings showed that using BIM and VE improves design modification and detailed data extraction, e.g., cost, schedule, etc. The outcome indicated the significance of using both BIM and VE to enhance project functionality, performance, and team coordination throughout the project lifecycle. This study provided the value of the integrated BIM and VE, including understanding the project requirements, improving team dynamics, seamless data exchange, and a comprehensive understanding of linking weighted and functional analysis to BIM processes and validated recommended project solutions. The proposed framework provided an option for virtually evaluating design changes and reducing errors during construction.

Key Words: Building Information Modeling, Case Study Project, Construction Schedule, Cost Control, Value Engineering

Introduction

The value engineering (VE) process presents opportunities to remove unnecessary costs while ensuring quality, reliability, performance, and improvements resulting from multidisciplinary teams' recommendations (Wao, 2015). VE defines a rigorous and structured effort to optimize the designed building features, materials, and equipment selections to achieve vital functions at the lowest life-cycle cost. The VE approach generates cost improvements without sacrificing the required project quality levels. Different levels of experts across the architectural, engineering and construction (AEC) industry have used VE effectively to improve decision-making (Wao et al., 2017). Ranjbaran and Moselhi (2014) presented an automated 4D-based VE model for design professionals, owners, and VE teams to assess and compare different design alternatives using multi-attribute criteria. The model was applied to a case study project to rank other options and choices. The results supported cost-driven decision-making with different design alternatives.

The execution of VE has been consistent in many construction projects beyond the planning, design, and post-construction phases including maintenance and operation (Pour et al., 2020). These factors affect the cost of construction projects which increases the difficulty of cost control and management. VE applications in building projects remain limited owing to the large scale of information exchange making it difficult to conduct a desirable VE process. The life cycle of building projects and the continuous increase in risk factors are not conducive to the development of VE (Wen, 2014). VE application alone is insufficient for effective cost control and schedule management. Therefore, there is a need to introduce building information modeling (BIM) to complement the effort.

Taher et al. (2019) investigated BIM-VE integration in the construction industry using a case study approach and at the design stage only. This paper aims to further this effort by providing a framework for using BIM and VE applications simultaneously during the design to post-construction phases using a case study approach. The literature review discusses VE, BIM and related integration of both.

Literature Review

Value Methodology

Several factors and roadblocks can lead to unnecessary costs. The team approach is a proven way to overcome these roadblocks and concentrates on problem-solving techniques to overcome obstacles (Jongsik & Seunguk, 2018). VE builds a cohesive team of self-motivated individuals committed to achieving common goals. The VE process, also called Job Plan, drives the team's planned VE effort, leading to improved decision making to realize the optimal expenditure of owner funds while meeting the required functions at the most favorable value. Simultaneously, the owner's desired tradeoffs, such as aesthetics, environment, safety, flexibility, reliability, and time, are considered (Wao et al., 2017).

The traditional VE job plan comprises of the following steps (Wao, 2015):

1. *Information phase*: This phase brings all team members to a standard basic level of understanding of the project, including tactical, operational, and specific aspects of the subject. Functional knowledge establishes the base case to identify alternatives and mismatches and sets the agenda for innovation.
2. *Function analysis*: This phase focuses on validating that the project satisfies the needs and objectives of the owner. The function analysis provides a more comprehensive understanding of the project by focusing on what it does and must do rather than what it should be. The team identifies value-mismatched function(s) to focus on improving the project value.
3. *Creativity Phase*: The team creates an array of ideas that provide a wide variety of possible alternative ways to perform the function(s) to improve the value of the project.
4. *Evaluation phase*: The team evaluates the alternatives using some criteria and select the most preferred alternatives from the list of options.
5. *Development Phase*: The Value Study team develops selected alternatives and low-, medium-, and high-risk scenarios, and offers these alternatives to senior management for consideration.

BIM and its Application

BIM has gained significant traction in the AEC industry. The BIM technology allows for a concise virtual design model to be digitally assembled and constructed. BIM helps AEC industry actors to visualizes a simulated building before actual construction. This pre-planning activity helps in identifying potential design, construction, and operational problems.

According to Azhar et al. (2011), BIM represents a new paradigm within the AEC industry; it encourages the integration of stakeholders' roles in evaluating the advantages and disadvantages of applying BIM methodology in the preparation and coordination of building designs and computational tools. To accurately measure BIM application capabilities in construction enterprises, a study proposed an evaluation framework model based on interval gray cluster analysis (Jongsik & Seunguk, 2018). The study results indicated that the proposed model could provide a new approach to improving application capabilities. The application of BIM supports construction cost estimation and lifecycle cost for critical decision-making in the early phase of building projects (Jaewook et al., 2020). A 3D-BIM on-site performance measurement system enables project managers to recognize performance or job-site productivity in real-time, making the BIM application a unique process to reduce waste at the project site (Baarimah et al., 2022). The AEC industry is rapidly accepting BIM applications to reduce costs, and time, and improve environmental sustainability.

A study benchmarked the current status of BIM implementations, organizational structures, training requirements, and strategies for companies and examined the expectation of BIM knowledge and skills (Kihong & Mojtaba, 2011). The findings supported BIM growth as an essential component of construction operations. The researchers provided a benchmark for measuring the transformation of BIM practices in construction companies over time and across different sectors. In addition, the study provided essential information that informs university construction curricular efforts. Another study investigated effort where not using BIM model (geometrical model) at tender/bidding stage may increase the digital gap throughout the project life (Bucknall, 2021). The study traced the benefits of receiving BIM/Geometrical models at procurement (tendering/bidding) phase to thorough design interrogation, enabled class detection, risk reduction & allocation, efficient quantity take-off and safe construction sequencing including optimization of biddability. The benefits included embracing digital collaboration during procurement phase and the design team’s willingness to share BIM models to support procurement. BIM can also be used to simulate important aspect of facility from the perspective of three geometrical dimensions of building (Ershadi et al., 2021). These dimension aspects include time (4D), cost (5D), energy (6D), sustainability (7D), safety (8D), lean construction (9D), and industrialized construction (10D). In their assessments, it was found that 4D, 5D, 8D and 9D BIM to be more significant during design and construction stages.

BIM and VE Integration

Controlling the construction schedule and cost are critical steps in ensuring a project's success and increasing its value (meeting the owner's requirements). Stakeholders have been widely applied BIM in construction projects to minimize total costs. BIM capabilities may present an excellent opportunity to facilitate the VE process from the early project phase. Baarimah et al. (2022) conducted a bibliometric analysis to ascertain the advantages of BIM and VE integration. The outcomes showed that VE and BIM help in decision-making concerning the cost-earned value and support increased prominence as mainstream topics associated with the construction industry.

The crucial phase in VE applications is the evaluation of generated alternatives with defined criteria. Designing an automated approach to evaluate and compare these alternatives helps stakeholders utilize multi-attribute criteria to integrate the designed models with visualization capabilities and easy decision-making processes. Demirdöğen et al. (2021) developed a maturity framework to facilitate the AEC industry and identify open challenges. The results indicated that BIM integration with VE is a prominent application for construction waste reduction. Al-Gahtani (2022) comprehensively reviewed recent VE studies to identify VE application challenges and probed the existing automation knowledge gap. The study identified solutions for owner value addition. According to Zhang and

Gohory (2022) proposed automated system, decision-makers need to enhance the design's ability to meet stakeholders' values and encourage synergy between the VE team and other project members. Another study used weighted evaluation technique to evaluate construction system in comparison with an alternative. The study recommended weighted evaluation technique as a safe approach for criteria scoring matrix for value alternatives (Agrama et al., 2014).

Research Methods

The study focused on providing a framework to harness BIM and VE applications during the design to post-construction phases using a case study project. The case study required a functional analysis system technique (FAST) which details how to display functions in a logical sequence to prioritize tasks and test their dependencies (Wao et al., 2017). The aim was to develop a framework for using BIM and VE processes to improve value, minimize cost, and schedule through an expanded model for alternative material selection and seamless information exchange. The specific objective was to determine VE and BIM effects on overall value propositions for the proposed case study project.

Integrated BIM-based VE Framework

Figure 1 shows the integration of the BIM-based VE automated framework into an integrated repository of a distinct database for design alternatives. The proposed framework contributes to the execution of alternative analysis by selecting suitable design alternatives.

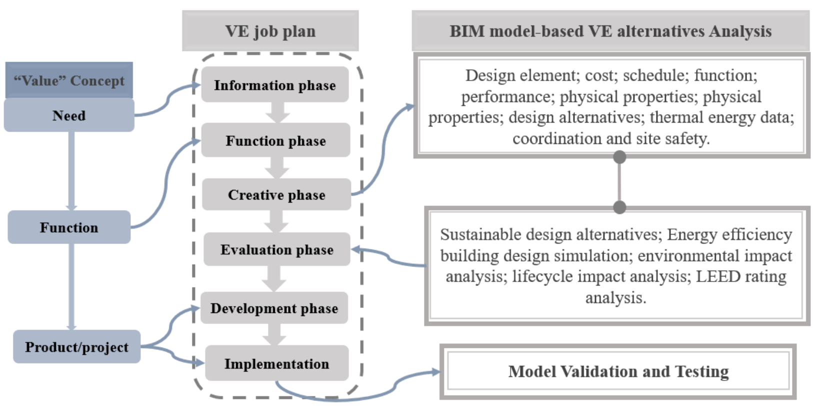

Figure 1. BIM-based methodology framework for integrating BIM and VE

The framework starts by implementing the VE job plan, including the information, function analysis, creativity, evaluation, and development phases. Automation of the framework was developed through 3D, cost (4D), and schedule (5D) models to facilitate smooth alternative generation. BIM models favors the elimination of old methods of importing all data into one drive/dropbox/desktop system (Amoah, 2022). The research supports the idea of a new system based on CAD-BIM integration with extended connection through automated platform to enable automatic linking with other application. The automated BIM Based framework serve as a platform for analyzing design alternatives and further extracting the cost, schedule, and energy-related data (6D), sustainability (7D), safety (8D), lean construction (9D) and possible industrialized construction (10D). The evaluation process was conducted using a case study. The case study included the development of a systemized procedure for the review and selection of design alternatives. The evaluation phase was conducted upon completing case study criteria and setting up platform to validate design alternatives.

The BIM-based automated VE approach for cost, schedule, and constructability reviews, aiding alternative material selection processes, is described in Figure 1. The flowchart presents the pathway for process review and material validation criteria. First, a 3D schematic model for the early design phase of the VE job plan was developed. The model presents an opportunity for the progress of these VE team meetings from the "Informational and Functional analysis" phase to the "Creativity and Evaluation" phase. The team further upgraded the model into a complete architectural model with building envelopes and created a structural model along with a mechanical, electrical, and plumbing (MEP) model, as illustrated in Figure 1. The process underscores the seamless interaction between the disciplines that conduct thorough constructability reviews and evaluations of the actual construction.

Case Study Building Project

The building for case study was a mixed-used Office and Laboratories building, named "Digital Futures building," located in Cincinnati, OH. Its footprint was 180,000 SF which included a concrete parking garage, basement, and six-story steel structures. It also included 1,350 underground parking spaces with 26 surface lot spaces. This building presented an opportunity to apply the VE and BIM integration process from the preconstruction phase to the construction phase because of its magnitude and team involved in its construction. Figure 2 illustrates its structural floor plan and 3D view.

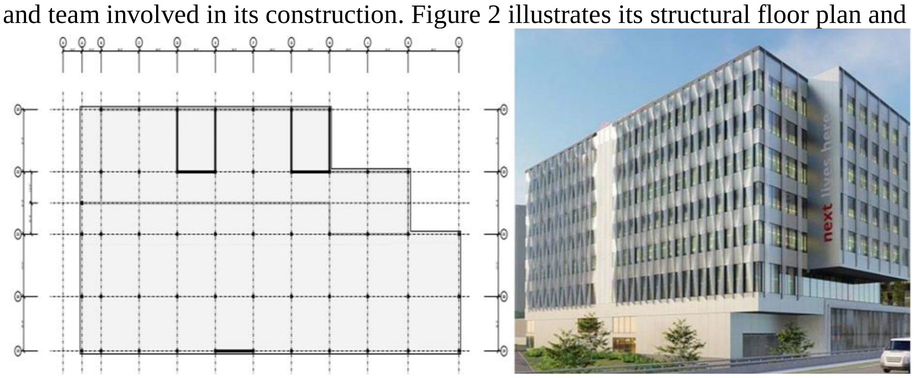

Figure 2. Typical structural floor plan and the 3D view of an ongoing "Digital Futures" project

Results and Discussion

Integrated BIM and VE can enhance project value, schedule control and cost reduction. Based on the results of this study, an empirical approach to improve project value, reduce cost, enhance schedule overruns, and increase overall project quality is proposed. The approach is discussed in the job plan.

Value Engineering – Information Phase

First, all associated data required to develop the BIM model (shown in Figure 2) were collected, and the 3D model was generated based on partial 2D plans, layout design, and other vital construction data. The 3D model made visual deliberations easier and improved the project's early design, planning, and construction. Generating the 3D model helped synchronize the imaginary view of the VE team's involvement in the exercise to measure the ideas developed. The model further served as a reference point for both cost estimate (4D) and schedule (5D), as in Fig. 4 and 5. The 3D model aided the team to resolve constructability issues prior to construction. The information assured the use of VE and BIM integration process and ensured that the project objective was evaluated throughout the stages of construction. Additionally, the method provided a visual alignment of the original data to ensure that the project preserved the intended value for the owner and stakeholders.

Value Engineering – Function Analysis Phase

The functions of the project elements were identified in the chosen case study to assist in analyzing the VE generation of design alternatives. Functional analysis was crucial in achieving the primary purpose of creating design alternatives. The technique of analyzing the options for the VE study provided a tool for extensive participation in the design and cost optimization of the project. The generation of alternatives was based on defined analysis criteria. Additionally, the decisions of the team resulted from the capacity of the design to accommodate the actual implementation procedure and the flow of information. The proposed criteria for this study included in the building model were cost, schedule, quality, appearance, and energy efficiency. Figure 3 presents the FAST diagram.

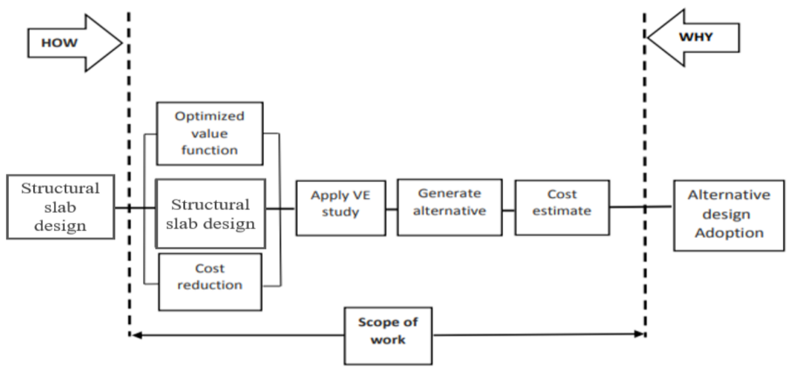

Figure 3. FAST diagram of the case study which shows the scope of the study.

Value Engineering – Creativity Phase

Creativity phase focused on generating alternatives. The BIM-based model served as a collaboration platform to assist VE team in visualizing and considering the merits and demerits of each alternative. Based on the FAST diagram, several alternatives were considered for further evaluation as in Table 1.

Table 1

Base Design and Alternatives

Base Concrete Slab Design	Alternative Concrete Slab Design
Cast-in-place concrete with Joist Slab System	1. Flat Slab Structural System with Drops 2. Band Beam Structural System 3. Two-way Concrete Slab & Beam Structural System

Value Engineering – Evaluation Phase

The evaluation process aligned each considered alternative and subjected it to strict proof of the value equation. The value (owner requirement) is multiplied by the risk (i.e., performance per cost index, design appearance, and stability). Refer to equation 1:

Equation 1: Value = (Performance / Cost) × Risk

In evaluating performance, attributes were determined to enable the scale to be measured and compared. Based on the equation, the higher the performance, the higher the value index generated; same applies to risk. Different projects have different characteristics depending on the project goals. Table 2 lists the performance attributes of the case, and the scale was categorized into five stages.

Table 2

Performance Attributes

Performance Attributes		Scale	Description
Project schedule/ Duration	The ability to meet the construction schedule: (Nov 23, 2021 – Sep 09. 2022)	5	Complete earlier more than by 4 weeks
		4	Complete earlier more than by 4 weeks or less
		3	Complete on Time
		2	Complete late by 4 weeks or less
		1	Complete late more than by 4 weeks.
Quality Index	Type of material and its maximum material lifespan and durability	5	Last 25 years or more
		4	Last 15 to 20 years
		3	Last 10 to 15 years
		2	Last 5 to 10 years
		1	Last 5 years or less

Table 3 presents the risk attributes of the project's suitability.

Table 3

Risk Attributes

Risk Attributes		Scale	Description
Cost Index	Increment/ reduction of Cost from the original cost	5	\$35.98/SF
		4	\$45.50/SF
		3	\$66.80/SF
		2	\$79.00/SF
		1	\$86.00/SF
Appearance	The Aesthetic Value of the design/exterior finishes	5	Premium
		4	Attractive
		3	Moderate
		2	Unattractive
		1	Very Unattractive

Because cost optimization was one of the goals, one of the attributes was to consider cost risk for each alternative; appearance was selected as the second attribute because of the owners' special needs.

BIM Application on the Case Study Project

The 3D models of the case study building were created (refer to Figure 5) based on the BIM methodology. A series of alternative design and material selection analyses were defined to serve as a bedrock for the project database. The BIM model (Figures 4 and 5) generated cost data, including quantities, cost estimates, and construction schedules. The team executed model integration and clash detection using Navisworks. The clash detection exercise aided in the smooth integration of various building components and systems, preventing unnecessary rework and waste during construction. The VE team resolved major constructability issues, leading to project time and cost reduction. Clash detection report showed 1805 clashes which were resolved before construction. The process used BIM capabilities to resolve the problems of material usage, handling, sequencing, scheduling, and cost issues. The BIM platform helped VE and other non-VE team members promptly exchange vital building information and data across all project phases.

Selected System: Flat Slab with Drop Panel

Cincinnati, Ohio

Data Release : Year 2022

Unit Cost Estimate

LineNumber	Description	Unit	Quantity	Total	Ext. Total	Components	Total %	%
032111600400	Reinforcing steel, in place, elevated slabs, #4 to #7, A615, grade 60, incl labor for accessories, excl material for accessories	Ton	454	$ 2,010.12	$ 912,594.48	Steel Rebars	34%	34%
033913500400	Curing, curing blankets, buy, 1" to 2" thick	S.F.	99000	$ 0.62	$ 61,380.00	Concrete	23%	2%
033113701500	Structural concrete, placing, elevated slab, pumped, 6" to 10" thick, includes leveling (strike off) & consolidation, excludes material	C.Y.	3555	$ 19.94	$ 70,886.70			3%
033113350350	Structural concrete, ready mix, heavyweight, 4500 psi, includes local aggregate, sand, Portland cement (Type I) and water, delivered, excludes all additives and treatments	C.Y.	3555	$ 130.68	$ 464,567.40			18%
031113352000	C.I.P. concrete forms, elevated slab, flat slab with drop panels, to 15' high, 1 use, includes shoring, erecting, bracing, stripping and cleaning	S.F.	104960	$ 10.85	$ 1,138,816.00	Formwork	43%	43%
				Total	$ 2,648,244.58			

4D

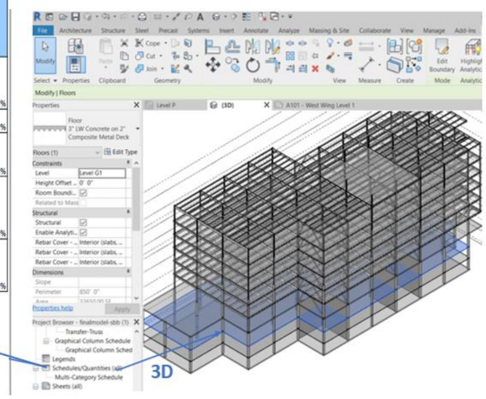

Figure 4. Transferring 3D - lightweight concrete floor on composite metal deck to 4D - Quantity takeoff and cost estimate

Item	Unit	Quantity	Labor Hours	Daily Output	Total Days
Reinforced steel, inplace, elevated slabs, #5, A615, grade 60, incl labor for accessories.	TON	455	12	3	157
Structural concrete, placing, elevated slab, pumped, includs leve & consolidation	C.Y.	3555	0.4	160	23
C.I.P. Concrete forms, elevated slab, flat slab with drop panels, 1 use, includes shoring, erecting, bracing, stripping and cleaning.	S.F.	104960	0.2	449	234

Schedule (5D)

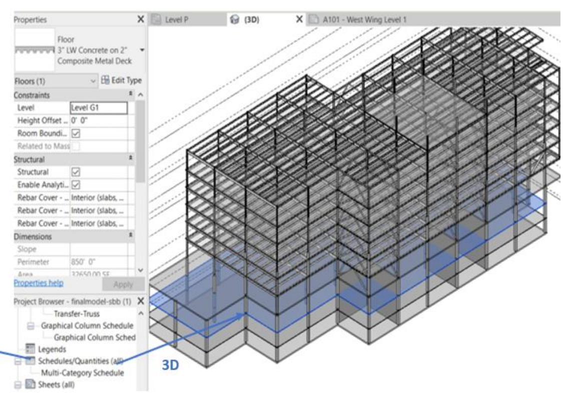

Figure 5. Converting 3D construction schedule to 5D

Conclusion

This study provided a framework for using BIM and VE applications to improve project value using a case study. Specifically, it examined the impact of using BIM with VE to improve information sharing and selecting appropriate design alternatives and decision-support models to assist the project team in evaluating identical design alternatives. This was to further the goal of Taher et al. (2019).

The research findings indicated that BIM and VE integration positively impacted projects and provided value to owners. The integration provided value to specific activities, such as team coordination, schedule control, cost control, quantity takeoff, estimation, and structural analysis which goes beyond Taher et al. (2019) which was only limited to cost reduction on structural elements. This study contributes to the field of BIM and VE integration by developing a systemized framework to facilitate a smooth process of decision-making capabilities for industry stakeholders. This is a true benefit of improving construction costs, reducing conflicts, improving team communication, and reducing project duration which eliminates manipulation of individual project team members.

References

Agrama F. A., Al-Nemr M. T., & Abdo M. A. (2014). Value Engineering for Low-Cost Housing Construction in Egyptian Expansion Urban. Advanced Research in Engineering Sciences.

Amoah K.B.O. (2022). Web-Based Building Information Modeling Data Exchange Standardization Protocols for the Architectural, Engineering, and Construction Industry. International Journal of Construction Engineering and Management 2022, 11(3): 65-77

Azhar, S. (2011). Building information modeling (BIM): Trends, benefits, risks, and challenges for the AEC industry. *Leadership. Manage. Eng.*, 11 (3), *241–252*.

Baarimah, A., Alaloul, W., Liew, M., Al-Aidrous, H., Alawag, A.& Musarat, M. (2022). Integration of building information modeling (BIM) and value engineering in construction projects: A bibliometric analysis. *Clim. Change*, 2021.

Bucknall, R.L. (2021). Getting closer to your supply chain. Retrieved from: https://ww3.rics.org/uk/en/journals/construction-journal/why-we-should-use-bim-at-tender-stage.html

Demirdöğen, G., Diren, N. Aladağ, H. & Işık, Z. (2021). Lean based maturity framework integrating value, BIM, and big data analytics: Evidence from AEC industry. *Sustainability*, 13 (18).

Ershadi, M., Jefferies, M., Davis, P., & Mojtahedi, M. (2021). Implementation of Building Information Modelling in infrastructure construction projects: a study of dimensions and strategies. International Journal of Information Systems and Project Management, 9(4), 43.

Jaewook, L., Hyuncheul, Y., Jinkang, L., Taehoon, H., Jimin, K. & Kwangbok, J. (2020). BIM-based preliminary estimation method considering the life cycle cost for decision-making in the early design phase. *Journal of Asian Architecture and Building Engineering*, 19:4, 384-399.

Jongsik, L. & Seunguk, N. (2018). Investigation of practitioners Perceptions for Developing Building Information Modelling (BIM) - Based Value Analysis Model. *Int. J. Civ. Eng. Technol*.

Kihong, K. & Mojtaba, T. (2011). BIM Experiences and Expectations: The Constructors' Perspective. *International Journal of Construction Education and Research*, 7:3, 175-197.

Pour, F., Seyedzadeh, S., Oliver, S., Rodriguez, S. & Dawood, N. (2020). On-demand monitoring of construction projects through a game-like hybrid application of BIM and machine learning. *Autom. Constr.*, 110, *103012*. https://doi.org/10.1016/j.autcon.2019.103012.

Ranjbaran, Y. & Moselhi, (2014). 4D-based value engineering. *Constr. Res. Congr, ASCE 2014*.

Taher, A., Rashid, I & Emad, E. (2019). Integration of Building Information Modeling with Value Engineering in Construction Industry-Case Study. *International Journal of Basic and Applied Sciences*, 8(4), 75-82.

Wao, J. (2015). A review of the value engineering methodology: Limitations and solutions for sustainable construction. In *55th SAVE International Annual Conference*.

Wao, J., Ries, R., Flood, I., & Kibert, C. (2017). Enhancing the Function Analysis and Identification Phase of the Value Engineering Methodology. In *57th SAVE International Conference*.

Wen, Y. (2014). Research on cost control of construction project based on the theory of lean construction and BIM: Case study. *TOBCTJ*, 8 (1), 382–388.

Zhang, L. & El-Gohary, N. (2022). Human-centered and BIM-integrated automated value analysis of buildings. *International Journal of Construction Management*.

Extracting BIM data to support a machine learning model for automated clash resolution

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Clash resolution is considered a critical step to resolve issues among the different disciplines for a construction design to be realized as expected. This step, however, continues to remain slow and manual which can significantly delay a project and drive-up costs. A combined machine learning model was proposed by Harode and Thabet (2021) to automate the clash resolution process. A large amount of labeled dataset is required to train and test the proposed model. The dataset is planned to be extracted from various industry-provided federated construction BIMs. Federated construction models are created from multiple subcontractor component models authored using different software. As a result, data is stored in various formats using different data structures making the extraction process difficult. In this paper, the authors demonstrate the use of commercially available software tools including iConstruct, Dynamo, and Talend to overcome this limitation and extract the necessary data. The paper first defines the required data structure followed by a data extraction process to capture required data from clashing elements in the federated BIMs. The paper also discusses a novel method of extracting end point coordinates and moveable area for clashing elements using bounding boxes. The paper concludes with future research directions.

Key Words: Design Coordination, Clash Resolution, Machine Learning, Data Extraction, IFC

Introduction

On any construction project, the coordination of mechanical, electrical, and plumbing (MEP) systems accounts for 6% of the total MEP cost (Hu et al., 2020). MEP coordination can be divided into two steps. In the first step, clash detection is performed and is focused on identifying MEP elements that occupy and compete for the same physical space. Clashes can either be detected manually using model walkthroughs, or automatically using Building Information Modeling (BIM) software tools such as Clash Detective from Navsiworks. In the second step, clashes are analyzed, filtered, classified, and discussed in coordination meetings to identify potential resolution strategies (Hu & Castro-Lacouture, 2019). Clash resolution remains a manual and slow process that relies heavily on the BIM coordinators' experience. One way to improve clash resolution is through the use of machine learning. Using machine learning to automate clash resolution has many benefits but requires a large amount of data to ensure its effectiveness and accuracy (Xu et al., 2021). Limited availability of data when training a machine learning model can limit its effectiveness due to model overfitting. Overfitting is a modeling error that introduces bias to the model making it too closely or exactly related to a particular set of data, and irrelevant to other data sets. The model may fail to fit additional data or predict future observations reliably. Therefore, effective development of the machine learning model requires a large amount of labeled dataset as input that relies heavily on capturing sufficient expert knowledge.

Harode and Thabet (2021), and Harode, Thabet and Gao (2022) proposed a machine learning model to effectively automate clash resolution with limited data. The proposed model uses a combined supervised and reinforcement machine learning algorithm to automate clash resolution. The supervised learning model will be trained using limited clash resolution data. This model is later improved upon by acting as pre-training data for the reinforcement learning model. The proposed algorithm is hypothesized to be faster, more efficient, and require less data input to resolve clashes compared to using supervised learning or reinforcement learning individually.

Selecting the appropriate features for training a machine learning model is an important step that needs to be conducted to ensure that the model generates better data relationships and is explainable and implementable (Harode, Thabet, & Leite, 2022). Using literature review and industry interviews with experts from several general contractors and mechanical contractors, Harode, Thabet and Leite (2022) identified 13 factors (or features) of a clash that are utilized by clash coordination experts to resolve clashes. These factors are summarized in table 1. To implement an effective machine learning model, the proposed model will require a reasonable size dataset containing factors and their values for different clashing elements. Using several case study BIMs, the authors extracted data for the 13 factors from clashing elements in these models and stored the data as shown in figure1. Factors 1 through 11 are specific to each clashing element, whereas, factors 12 and 13 are common between the clashing elements. A detailed description of these factors is provided by Harode et. al., 2022. Example values for each factor are provided in figure 1 to illustrate the types of data that were captured from the case study models.

Table 1
List of factors (features) identified

S. No.	Features	S. No.	Features
1.	Start and End Point (X, Y, Z)	8.	Clashing Element Rigidity
2.	Element Dimensions	9.	Number of Clashes
3.	Clashing Element Type	10.	Moveable Area
4.	Clashing Element System Type	11.	Number of Connections
5.	Clashing Element Constrained Slope	12.	Critical Element in the Clash
6.	Insulation Size	13.	Location of the Clash
7.	Clashing Element Material		

With reference to figure 1, area 1 shows the list of 13 factors identified by Harode et al. (2022). In this paper, the authors explore, and test data extraction methodologies and tools used to capture data from the case study BIMs to populate area 2. This data will later be used to train the proposed machine learning model. Area 3 is the label heading for the machine learning model and area 4 represents potential options for resolving each clash acting as labels for the training dataset. Data for area 3 and 4 are not part of the data extraction process detailed in this paper and will be populated by the authors for each clash based on authors experience, discussion with the industry experts, and comparison with the final coordinated as-build models.

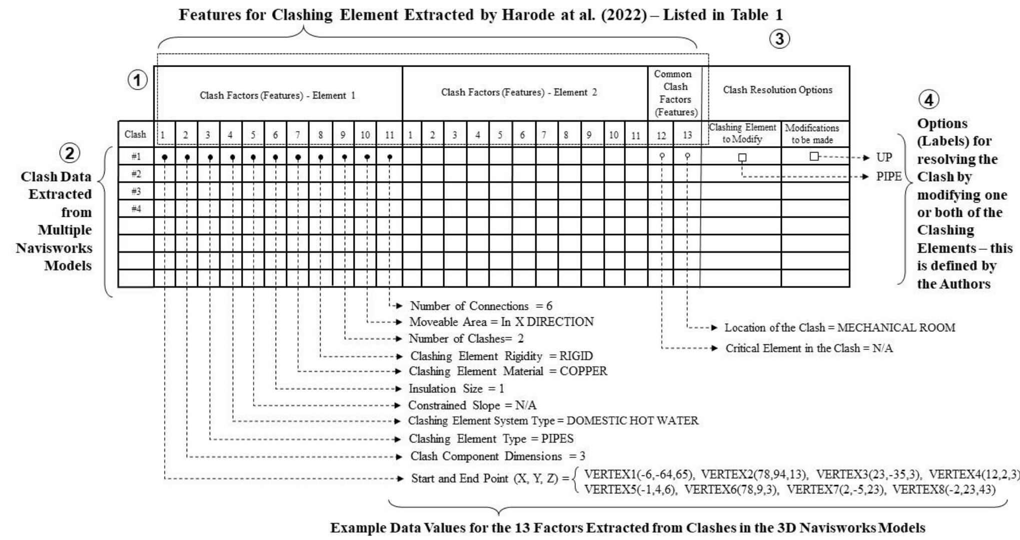


Figure 1. Organization of Factors and their values, and labels and their values for training the machine learning model proposed by Harode and Thabet (2021).

Xu et al. (2021) concluded the need to make construction data more available to support the development of Machine Learning in the construction industry. Given that Machine Learning is a highly data-driven process, they highlighted that data availability plays a key role in its implementation. They also concluded that difficulty in construction data acquisition and manual annotation is one of the limiting factors of Machine Learning adoption in construction. Bilal et al. (2016) while talking about the pitfalls of big data in the construction industry addressed fragmented data management practices as a cause for slower adoption of trends like big data. As a move forward towards effective data extraction from BIMs, Ignatova et al. (2018) explored and compared the extraction of embedded BIM data in the Revit model using standard Revit tools, SharpDevelop code editor, and Microsoft Visual Studio Plug-in. The data was extracted to support the future development of smart cities. Kim et al. (2013) also developed a framework that extracted data stored in BIM models to automate the generation of construction schedules. This framework was tested using a BIM model of a basic building. To improve the data extraction process for BIM models, Guo et al. (2020) developed a method to automatically generate SPARQL (Standard Query Language and Protocol for Linked Open Data and RDF database) queries based on users' data requirement. This method was validated using multiple case studies in which effective and accurate SPARQL queries were generated using the proposed method to facilitate data extraction. Kadcha et al. (2022) proposed an integrated solution using Dynamo and Power BI to facilitate data extraction and visualization. The data was extracted in the AEC domain of cost extraction, clash detection, change detection and plan extraction. Dynamo was used to extract data from the BIM models while Power BI was used to visualize the extracted data.

On a majority of construction projects, discipline component models (architecture, structure, HVAC, mechanical pipe, electrical, plumbing, fire protection, etc.) are first created using different model authoring tools, then integrated into a federated model. This creates challenges in extracting data from the federated model due to different data structures, formats and naming conventions used by the different source discipline models. Therefore, the research question that this paper is focused on answering is how can clash data from federated model created using models authored by multiple software be effectively extracted to support creation of machine learning models for clash resolution? To answer this question, the authors explored and tested multiple software tools that can be utilized to facilitate extracting data for the 13 factors identified from federated Navisworks models. Tools tested included, iConstruct (https://iconstruct.com/), Dynamo (https://dynamobim.org/), and Talend Studio (https://www.talend.com/). iConstruct is an add-on to Navisworks and provides users with a large suite of tools to manage design and construction information. Users can export custom-built clash reports using the Clash Report tool or export the Navisworks model as IFC with desired properties using IFC Exporter. Dynamo allows users to interact with Revit API using Visual Programing to process data, generate geometry, and extract information. Finally, Talend Studio was used to create a data pipeline that can combine data in several Excels into a single Excel spreadsheet using a common data value. Talend can be used to preprocess data from any type and any number of data sources and export the data to a user-defined format.

The following section discusses the detailed research steps adopted by the authors to extract values for the 13 factors from several case study BIMs. The research focused the analysis on clashes between ducts and pipes only, using several Navisworks models of various case studies provided by industry partners. The paper concludes with a discussion and conclusion drawn from the tested data extraction process.

Research Steps

Figure 2 summarizes five main steps involved in the data extraction process.Using Clash Report function of iConstruct (1), clash test data including clash test name, clash group, clash name, and clashing element GUIDs were exported to an Excel file (ClashData.xlsx). Using the IFC export function of iCosntruct (2), the Navisworks model is exported and saved as an IFC file along with element properties like element GUIDs, element system type, element material type, area of the element, and element type. It should be noted that these element properties should be pre-defined in the Navisworks models used so that they can be exported with the model and used in the anlysis. The IFC model file is imported into Revit (3) and Dynamo (4) was used to extract the 13 clash factors to a second Excel file (ElementData.xlsx). Using the GUID parameter common between the two Excel files, data from both files (1-3 and a-e) are combined using the tMap function of Talend Studio (5). To test the proposed data extraction tools described in figure 2, the Navisworks model for a medical facility case study is selected. The federated model is generatred from combining several component discipline models with varying file formats including *.nwc, .dwg, and .dwfx*.. Parameter data defined in figure 2 forclashes between duct and pipe elements are identified and extracted using the tools and steps described. The following subsections provide a more detailed description of how each tool was used to extract the required data.

Using iConstruct to export Clash Data and IFC model

The Navisworks model for the medical facility case study was pre-loaded with clash tests conducted by the general contractor during the design coordination phase. iConstruct's clash report tools allow users to export clash data in PDF or Excel format. These clash reports are completely customizable and can include any data embedded into the clash elements.. In the proposed methodology, the clash report tool was used to custom-create an Excel template to export different clash information including the clash name, clash test group, and clashing elements GUIDs. The exported clash report (ClashData.xlsx) will be utilized to identify a clashing element using their GUIDs in the IFC model.

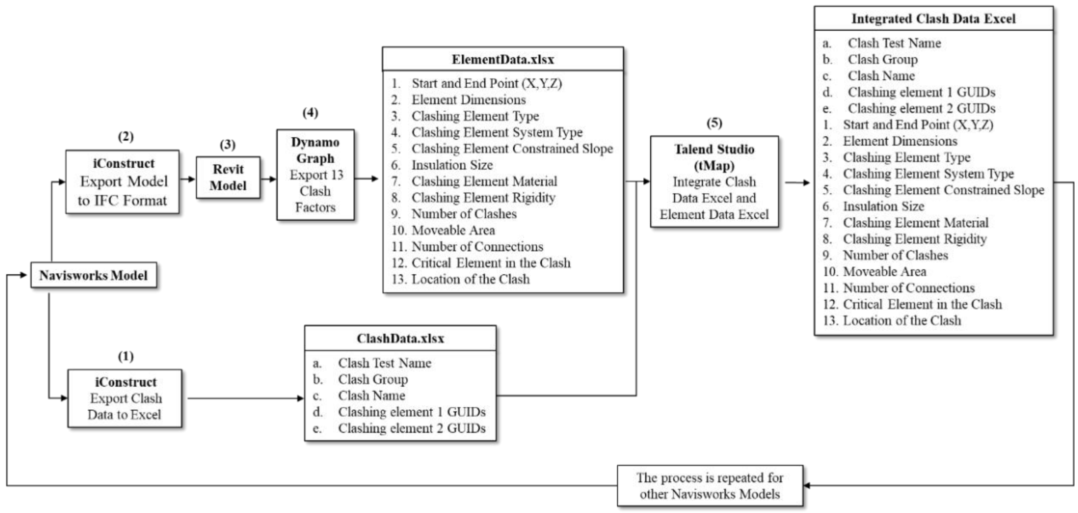
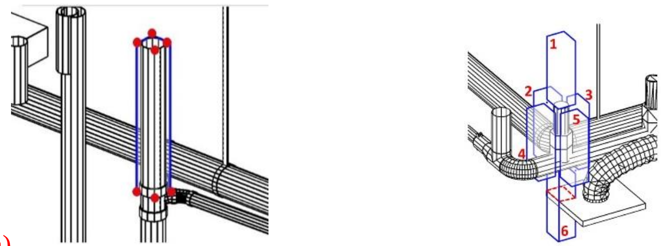


Figure 2. Proposed Methodology to extract clashing element data.

While retrieving data from BIMs, the lack of use of BIM authoring tools with standard file formats creates an interoperability issue and results in significant challenges to extract the data using common extraction rules. Different sub-contractors utilize different model authoring tools leading to the use of different data structures and property naming conventions. To overcome these challenges, the Smart IFC Export tool of iConstruct was used to export the Navisworks model to an IFC file along with the desired properties. In this proposed methodology the mechanical and plumbing models of the medical facility are exported as IFC files along with additional properties such as GUID, Material, Type Area, Layer, Source File, and Description in Navisworks.

Using Dynamo to extract and export factor data from the IFC model

Using the Revit model, Dynamo Graphs is used to extract values for the 13 clash factors from clashing elements identified by their GUIDs. Various spatial properties of clashing elements such as their start and end points and the moveable area around the clashing elements need to be extracted. Since duct and pipe elements in the converted IFC to Revit model did not originate from a Revit component discipline model, they are missing geometric parameters like element line segments and end point coordinates, and could not be extracted directly. The authors used the concept of bounding boxes to extract the missing spatial properties. Using Dynamo, bounding boxes were first created around all clashing elements and then converted into cuboid geometry. As shown in figure 3a, the eight vertices of these cuboids were extracted as the endpoint coordinates of the clashing elements. To identify available free space around each clashing element, six similar bounding boxes are created and placed around the boundaries of the element. These bounding boxes were then checked for possible clashes with other surrounding elements. If a bounding box returned a true value this indicated that another element interfered with the bounding box. All six sides around the clashing element were checked for other elements within its vicinity to determine feasible options to resolve the clash. Figure 3b shows the 6 bounding boxes surrounding the clashing element. The clashing element cannot be moved in the direction of bounding box “6” because it is clashing with the air terminal restricting the movement of the clashing element in that direction.



(a) (b)

Figure 3. (a) Bounding box around an IFC element (blue) along with eight vertices (red). (b) Six bounding boxes surround the clashing element.

Because original component models were authored using different software platforms, embedded data in each model has a different structure hierarchy with different naming convention adopted resulting in inconsistent names for the same parameters. This did not allow for a straightforward approach to extract required parameter data of clashing elements from the federated model. This limitation is partially overcome by converting the Navisworks model into IFC resulting into a standardized data hierarchy as per IFC schema. Limitation of different naming convention of properties name could not be overcome required the authors to manually identify property names used by each component model and manually input the names into the Dynamo Graph script to be able to extract their values. The extracted 13 clash factors using Dynamo are exported to an Excel file (ElementData.xlsx) along with a unique GUID value corresponding to each of the clashing element. As discussd in the next step, this GUID is used to combine the ClashData.xlxs with ElementData.xlsx.

Using Talend to combine the two Excel data

Talend Studio is a software tool that can be used to build data pipelines focused on data integration, data cleaning, data pre-processing, and data management. Talend can handle large datasets from multiple data sources and create replicable pipelines that can speed up the data processing time. In this paper, Talend is used to combine data from the ClashData.xlxs with data from the ElementData.xlsxinto a single Excel file. This step can also be performed using the "VLookUp" function in Excel or writing a custom code in python. The use of Talend in this paper has been prompted by the need to perform data integration and data cleaning on large datasets when thinking about the practical implementation of machine learning. The use of Excel is limited to smaller datasets and file format (.xlsx) and python requires users to have experience with the coding language. To overcome these limitations, the authors in this paper have tested the Talend Studio software. Talend provides a graphical user interface platform that can be used to create pipelines for data integration, transformation, and pre-processing. It is also capable of handling big data more effectively making it a more powerful and more efficient replacement for Excel and python when handling a large amount of data commonly generated while performing design coordination on larger projects. In this paper, a relatively small dataset is used to test the proposed methodology. But in a practical scenario, while training a machine learning algorithm, thousands of rows of data are required. Therefore, the authors decided to explore the tools that can be utilized to work with big data for practical industry implementation.

Talend's *tMap* component can transform and route data from multiple sources to a single destination making it an ideal candidate for data integration using the two Excel files. tMap's mapping capabilities allow for defining the data routing and transformation of the final data. Two or more data sources can be combined using a common column as a relationship link. Users can export combined files in the format of their choice. Two comma-separated file for each of the two Excel files

(ClashData.xlsx and ElementData.xlsx) are generated and imported into Talend. Using the tMap component, the GUID 1 value for the first row of data in the ClashData.csv is read. This GUID value is then searched in the ElementData.csv and the row associated with this GUID value is copied and merged to the end of the first row of the Clash Data Excel spreadsheet. Similarly, the row corresponding to the GUID 2 value in the ElementData.csv is searched and merged to the end of the first row in the ClashData.csv adding the clashing elements BIM and spatial data to the ClashData.csv. This process is repeated for all rows in the ClashData.csv. The new Excel is saved with the name IntegratedClashData.xlsx as shown in figure 6b completing the data integration process.

Results

Table 2 shows an example of data collected for two clashes using the proposed workflow. The clash factor number in the table corresponds to the factors shown in figure 1. To understand how machine learning will be utilized to automate clash resolution, the table is divided horizontally into two sections. The Clash Factors representing required input or *Features*, and Clash Resolution Options representing required output or *Labels*. Clash *Features* contain the information for each clash that clash coordination experts will look for before making the decision on how to resolve the clash as discussed by Harode et al. (2022). This information includes information regarding individual clashing elements (Features 1 through 11) and information regarding the clash as a whole (Feature 12 and 13). Clash *Labels* comprise information on how the clash will be resolved. Examples of *Labels* may include element priority, direction of movement, and angle of sloping the element. This data for the *Labels* is decided by the authors based on experience, discussion with the authors, and extracting results from coordinated final as-built models.

Table 2
Sample clash data

Clash Factors (Features)				
Clash Factor	**Clash #1**		**Clash #2**	
	Element 1	**Element 2**	**Element 1**	**Element 2**
1	-165.849, -94.920, 29.241, -165.849, -92.253, 29.241, -170.536, -92.253, 29.241, -170.536, -94.920, 29.241, -165.849, -92.253, 28.074, -165.849, -94.920, 28.074, -170.536, -94.920, 28.074, -170.536, -92.253, 28.074	-168.897, -95.764, 29.276, -168.897, -93.457, 29.276, -169.074, -93.457, 29.276, -169.074, -95.764, 29.276, -168.897, -93.457, 29.099, -168.897, -95.764, 29.099, -169.074, -95.764, 29.099, -169.074, -93.457, 29.099	-234.549, -125.611, 28.986, -234.549, -121.923, 28.986, -237.216, -121.923, 28.986, -237.216, -125.611, 28.986, -234.549, -121.923, 27.653, -234.549, -125.611, 27.653, -237.216, -125.611, 27.653, -237.216, -121.923, 27.653	-232.937, -122.874, 29.089, -232.937, -122.697, 29.089, -235.468, -122.697, 29.089, -235.468, -122.874, 29.089, -232.937, -122.697, 28.911, -232.937, -122.874, 28.911, -235.468, -122.874, 28.911, -235.468, -122.697, 28.911
2	3	1	3	2
3	Ducts	Pipe	Ducts	Pipe
4	Exhaust Air	Domestic Hot Water	Exhaust Air	Gravity Pipe
5	No	No	No	Yes
6	0	1	0	0
7	Sheet Metal	Copper	Sheet Metal	Cast Iron

8	Rigid	Rigid	Rigid	Rigid
9	2	1	2	1
10	In X Direction	In -Z Direction	In X Direction	In Y Direction
11	2	2	2	2
12	N/A		N/A	
13	Mechanical Room		Mechanical Room	
Clash Resolution Options (Labels)				
Element to Modify	Element 2		Element 1	
Modification to be made	Up		Left	

The objective of any machine learning algorithm is to identify the relationship between the two sections of table 2. During the training phase of the machine learning model, the algorithm will be provided with two inputs, Clash Factors (*Features*) for all the clashes identified and their Clash Resolution Options (*Labels*). The algorithm will then attempt to identify an equation that maps the values of Clash Factors (*Features*) to their corresponding Clash Resolution Options (*Labels*) by assigning weights to these features. The weight of each factor is calculated by minimizing the loss function (e.g. squared mean error) between the predicted and actual labels for the clashes in the training data set. For testing the accuracy of the trained machine learning model, the algorithm is provided a different set of clash factors and the predicted labels are compared with the actual labels to assess accuracy.

Discussion and Conclusion

Extracting, integrating, transforming, and cleaning large amounts of data is an essential step in machine learning. As we continue the research to explore how machine learning can be used to automate clash resolution and improve the process, similar efforts need to be made to explore tools that can facilitate extraction of required data. The use of machine learning for construction applications is currently challenged by the limited availability of sufficient relevant data that can be defined as training data for machine learning implementations. When available in models, data is often present in a fragmented inconsistent format due to the use of multiple authoring software tools resulting in data embedded using different data structures and different naming conventions. To overcome these limitations and to support the implementation of the machine learning algorithm proposed in Harode and Thabet (2021), the authors have explored and tested a proposed workflow that utilized several commonly available off-the-shelf technology tools, including iConstruct, Dynamo Graph, and Talend, to extract data from Navisworks models. The proposed workflow is focused on extracting the required data to create the necessary dataset of features and labels required for the implementation of a proposed supervised-reinforcement machine learning model for automation of clash resolution. The required data being extracted is based on 13 clash factors considered by industry experts while resolving clashes identified using literature reviews and industry interviews conducted by Harode, Thabet and Leite (2022). The proposed workflow for data extraction was tested on a single Navisworks model with a small-size dataset. The workflow can also be scaled to extract a larger dataset using multiple models, a scenario more suitable for the development of an effective machine learning model. The authors utilized a novel method to extract spatial properties namely end point coordinates of the clashing elements and moveable area around the clashing elements using the concept of Bounding Boxes. This novel method can be utilized to extract spatial information for the clashing elements that are not authored using Revit and/or do not have a line element associated with them.

The following are several future steps that are being investigated and implemented to support the machine learning model proposed by Harode and Thabet (2021): (1) extract a larger parameter data set from multiple Navisworks models, (2) each row in the figure 1 will be populated with a potential clash resolution options (*Labels*) completing area 3 and 4, (3) the data will be preprocessed (scrubbed, dimensionally reduced, encoded, standardized, etc.) to make it more suitable for implementation of the Machine Learning algorithms, (4) a Supervised Learning algorithm will be trained using this data to predict potential clash resolution options, (5) the model developed using the Supervised Learning algorithm will be improved upon by using Reinforcement Learning to improve the effectiveness of the automation model for clash resolution, and (6) the improved automation model will be tested for effectiveness and efficiency.

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References

Bilal, M., Oyedele, L. O., Qadir, J., Munir, K., Ajayi, S. O., Akinade, O. O., Owolabi, H. A., Alaka, H. A., & Pasha, M. (2016). Big Data in the construction industry: A review of present status, opportunities, and future trends. *Advanced engineering informatics*, *30*(3), 500-521.

Guo, D., Onstein, E., & Rosa, A. D. L. (2020). An approach of automatic SPARQL generation for BIM data extraction. *Applied Sciences*, *10*(24), 8794.

Harode, A., & Thabet, W. (2021). Investigation of Machine Learning for Clash Resolution Automation. *EPiC Series in Built Environment*, *2*, 228-236.

Harode, A., Thabet, W., & Gao, X. (2022). An Integrated Supervised Reinforcement Machine Learning Approach for Automated Clash Resolution. Construction Research Congress 2022,

Harode, A., Thabet, W., & Leite, F. (2022). Feature Engineering for development of a Machine Learning Model for Clash Resolution. *EPiC Series in Built Environment*, *3*, 398-406.

Hu, Y., & Castro-Lacouture, D. (2019). Clash relevance prediction based on machine learning. *Journal of computing in civil engineering*, *33*(2), 04018060.

Hu, Y., Castro-Lacouture, D., Eastman, C. M., & Navathe, S. B. (2020). Automatic clash correction sequence optimization using a clash dependency network. *Automation in Construction*, *115*, 103205.

Ignatova, E., Zotkin, S., & Zotkina, I. (2018). The extraction and processing of BIM data. IOP Conference Series: Materials Science and Engineering,

Kadcha, Y., Legmouz, D., & Hajji, R. (2022). AN INTEGRATED BIM-POWER BI APPROACH FOR DATA EXTRACTION AND VISUALIZATION. *International Archives of the Photogrammetry, Remote Sensing & Spatial Information Sciences*.

Kim, H., Anderson, K., Lee, S., & Hildreth, J. (2013). Generating construction schedules through automatic data extraction using open BIM (building information modeling) technology. *Automation in Construction*, *35*, 285-295. https://doi.org/https://doi.org/10.1016/j.autcon.2013.05.020

Xu, Y., Zhou, Y., Sekula, P., & Ding, L. (2021). Machine learning in construction: From shallow to deep learning. *Developments in the built environment*, *6*, 100045.

Evaluating the Quality of Experience of Supplemental Instructional Videos

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Evidence shows that the college-age generation prefers learning by video to all other methods. However, many instructional videos produced by faculty and staff amount to little more than recorded lectures, causing students to report that they are long, dull, low-quality, and ineffective. As part of a broader study on object-based learning, this paper reports the attitudes that construction management students have toward a popular type of instructional video called supplemental instructional videos (SIVs). SIVs are designed to aid and reinforce primary learning materials and methods, not replace them or merely enhance them. The SIVs were produced by the instructors in accordance with an interdisciplinary curation of the latest literature covering the proper design and development of instructional videos. Data were collected using mixed methods and the Quality of Experience (QoE) strategy, relying on surveys and interviews to draw conclusions about student perspectives. Overwhelmingly, participants stated their preference for SIVs and reported that they improved their understanding of the subject matter. In spite of this, surprisingly, students were divided as to whether the SIVs had any real impact on their performance in terms of grades. The research also confirmed that SIVs are most appropriate for complex learning topics.

Key Words: Construction Education, Instructional Videos, Quality of Experience

Introduction

In 2005, Leonard Bernold (2005), a construction professor and researcher at North Carolina State University, documented the complaint of one undergraduate construction student: “How can you expect me to read something when I don’t understand it... In my job, I will not be required to write because I will work on a construction *sight* [sic]” (Bernold, 2005, p. 538). While Bernold was using this student’s frustration to illustrate the well-documented shortcomings of the traditional, reading-and-lecture-based learning method in construction education (e.g., Hoxley & Rowsell, 2006), it also reflects the simple reality that many undergraduate construction students find unassisted readings on unfamiliar topics to be challenging, often preferring to avoid them altogether. In 2018, Pearson Education commissioned a national, online survey aimed at understanding the differences in educational interests, outlooks, and values of Millennials (individuals born between 1980-1994) and Generation Z (individuals born between 1995 and 2015), who now constitute the majority of undergraduate students. Responses from 2,587 individuals ages 14 to 40 revealed that Generation Z prefers YouTube over all other learning methods listed in the survey, including books, interactive group activities, and learning apps and games. This study confirmed previous research by Chan (2010), who found that college students preferred video to textbooks. Chan noted that "video instructions are favorable to these university students and have a tremendous potential as a supporting tool for formal learning beyond the traditional classroom setting" (Chan, 2010, p. 1317). The Pearson survey also showed that Millennials still prefer books to YouTube by a small, 5% margin (Pearson Education, 2018).

Hypothesizing that future generations are likely to continue favoring video-based learning over more traditional, reading-based methods, researchers across fields have begun to explore a new pedagogical alternative called object-based learning (OBL). OBL is an active, student-centered teaching approach that relies on digital educational resources called learning objects (LOs) to facilitate tailored learning experiences for a specific audience (Wiley, 2002). LOs include a wide array of e-learning-based instruments such as digital images, animations, photographs, and videos. Currently, one of the most common types of LOs is instructional videos (Kay, 2012). Instructional videos fall into four categories: lecture-based, enhanced, worked examples, and supplementary (Kay, 2014). Lecture-based are the most common and basic. They are recordings of classroom lessons. Enhanced videos are designed to be motivating and exciting, helping students to take an interest in the subject matter. Worked examples are procedural in nature, typically used to guide students step-by-step through calculations or a process. Supplemental instructional videos (SIVs) are provided to complete the learning experience, either as introductory tools for unfamiliar concepts or to fill any gaps in understanding left by readings or lectures. Of the four, SIVs are recommended due to their ability to provide greater educational value and higher cognitive learning outcomes (McGarr, 2009).

Because the OBL approach is still relatively new, fundamental questions about the educational impact of SIVs remain unanswered, including how students feel about SIVs as part of their curriculum. The aforementioned 2018 Pearson Education survey suggests that students in rising generations have an affinity for instructional videos, however, the exploratory survey is only a starting point, useful for identifying a general trend, but far too broad in scope to provide targeted guidance for instructors working in formal classrooms. Hence, many academic fields need more domain- and intervention-specific research. Construction management is no exception. This paper helps fill this gap by presenting the findings of an explanatory investigation of CM students' perceptions of SIVs which were made to support traditional reading materials. Surveys and interviews were used to evaluate how students' quality of experience (QoE) was related to the use of SIVs in a CM classroom.

Literature Review

A limited number of studies have been published that consider how construction management (CM) students feel about instructional videos. In 2006, Hoxley & Rowsell researched the best way to use video with lectures. Their survey showed overwhelmingly that 98.6% of their construction students supported videos being used and generally preferred them over reading a book. Hoxley & Rowsell also found that instructional videos are most helpful to students when used with a concentration aid, like a quiz, and if "the main purpose of the lecture is to deliver technical detail, then this is certainly best delivered after the viewing of the video" (Hoxley & Rowsell, 2006, p. 121). The findings from the Hoxley & Rowsell (2006) study are largely confirmed by Cherrett, et al. (2009), who reported that 75% of second-year undergraduate students in their study stated that video had enhanced their learning experience with safety topics. They cautioned instructional designers and practitioners that passively viewing a video is not sufficiently stimulating. Students must actively engage with the content presented by the videos. Liu & Hatipkarasulu (2014), in their research on building information modeling (BIM) education, found that providing instructional videos to support complex procedural instructions seemed to be effective. They reported that instructional videos were particularly beneficial for students who were behind in their work. In agreement with Hoxley & Rowsell (2006), survey data indicated that students felt that content delivered by video was beneficial. However, like Cherrett et al. (2009), Liu & Hatipkarasulu warned that the instructional videos alone were insufficient in providing a deep understanding of the subject matter. Wong et al. (2018) experimented with video-based learning in a CM course utilizing a blended teaching model (i.e., both in-class and online). Seventy-six students were taught using the model and then surveyed. The study found that "students were satisfied with [the] design and content of the instruction videos" and "considered e-learning approach useful because it allows them to control their pace, time, and location for learning" (Wong et al., 2018, p. 1). Most recently, Zaneldin et al. (2019) studied undergraduate CM student satisfaction in response to course topics being taught with instructional videos. Following the study, 67 students were questioned with an online survey administered through the university learning management system (LMS). Overall, students were "satisfied with the contents of the instruction [*sic*] videos and benefited from these videos" (Zaneldin et al., 2019, p. 475). The students commented that they preferred the blended model that included online instructional videos because they had greater access to course content. Notably, of these studies mentioned, none clearly defined the type of instructional video administered or even provided satisfactory descriptions of the video themselves (e.g., recorded lectures, written examples, or narrated animations). Nor did they provide sufficient qualitative details regarding the quality, pace, engagement, and duration of the videos.

Research Questions

Building upon previous research, this study was aimed at exploring the perceptions that CM students have toward supplemental instructional videos (SIVs). Specifically, this study asked:

- Research Question 1 (RQ1): Do CM students feel that the use of SIVs as supplemental, educational tools for traditional learning materials (i.e., readings) improves their understanding of course subject matter?
- Research Question 2 (RQ2): For which construction topics (e.g., plumbing, foundations, framing) do CM students feel SIVs are most helpful?
- Research Question 3 (RQ3): Are CM students satisfied with the quality, pace, engagement, and duration of the SIVs as the literature recommends?

Methods

Surveys and interviews were used to investigate CM students' opinions of SIVs. Consistent with previous research on video- and multimedia-based instruction (Ljubojevic et al., 2014), the Quality of Experience (QoE), a strategy commonly used in customer service and telecommunications, was deployed to measure students' subjective impressions of instructional videos. The QoE is defined as "the degree of delight or annoyance of the user of an application or service. It results from the fulfillment of his or her expectations with respect to the utility and/or enjoyment of the application or service in the light of the user's personality and current state" (Le Callet et al., 2012, p. 6). Modeling Ljubojevic et al. (2014), who evaluated the QoE "to investigate [the] efficiency of use of supplementary video content in multimedia teaching" (p. 275), a survey was given to participants to evaluate their QoE with SIVs. The survey also asked students to rate the quality, duration, and pace of the instructional videos. Survey questions were composed of both closed-ended, ordinal questions on a traditional five-point Likert scale and a few open response follow-up questions. Following the survey, a short, approximately five- to ten-minute interview, was conducted one-on-one with all participants to gain further explanatory insights into the students' QoE. Each interview was semi-structured, allowing for some deviation from a set of five predetermined, guiding questions that asked participants to describe their experiences with and perceptions of the SIVs. The interviews were conducted remotely using Zoom web conferencing software. The Zoom platform was also used to audio-record and transcribe the interviews; the computer-generated transcripts were then edited for accuracy. The survey was piloted under real conditions by three current undergraduate CM students in the same department who were not participants in the study. All research activities were reviewed and approved by the Institutional Review Board (protocol 19-853).

Course, Population, and Sample

The study was conducted at a large, public university in the United States in a second-year course called Residential Construction Technologies in which students critically examined emerging construction technologies and compared them with their more conventional alternatives. The course was structured to introduce innovative construction technologies (e.g., solar roof tiles, condensing storage water heaters, ZIP framing systems) each week for twelve consecutive weeks of the semester. Short SIVs were produced for each of the emerging technologies to aid with pre-class readings on their design and function. Each student in the class was assigned a random set of six SIVs throughout the semester. The SIVs were distributed through the university learning management system with all other course assignments. Participants of the study were instructed to watch the SIVs alone, before class, and before completing the course readings that they were designed to support. All 46 students in Residential Construction Technologies were invited to participate in the study. 42 students completed surveys and participated in follow-up interviews for a response rate of 91%. Participants were predominantly male (n = 36; 86%) and composed almost entirely of Building Construction majors (n = 41; 98%), proportionally representing the current overall population of undergraduate students in CM classes at the university. A single study participant was majoring in Real Estate (2%). Participants of the study were primarily in their second (n=10; 24%), third (n=17; 40%), and fourth (n=12; 29%) years of school. Very few were in their first year (n=1; 2%) or fifth year (n=2; 5%).

Supplemental Instructional Videos

The SIVs for the course were produced by the instructor in compliance with a synthesis of interdisciplinary guidelines from the literature (Barnes, 2021). Hence, they were short (i.e., about three minutes each), narrated with a script, focused on a single topic, and rendered in high definition with only high-quality audio and visual elements. Each SIV was designed and produced by the same instructor teaching the course and made to be engaging for an undergraduate audience. They were organized, clear, purposeful, narrated with a personalized, first-person voice, interactive (i.e., incorporated guiding quiz questions), direct, relevant, and paced for maximum learning and engagement. All SIVs were developed with a home license of TechSmith Camtasia 2018. Visual and audio material came from open-access and license-free sources such as Pixabay.com, the YouTube Audio Library, and FreeSounds.org. A standardized preproduction, production, and review process was used to ensure compliance with best-practice guidelines, save time, and make each video qualitatively consistent with the others. The total production time of each video averaged just under four hours from writing the script to the final rendering.

Analysis

Survey responses were exported from Qualtrics into SPSS (version 25) for data management and analysis. All qualitative data were selectively coded for themes that provided additional insight into closed-ended survey questions. For RQ1 and RQ3, frequencies and descriptive statistics were calculated for corresponding closed-ended survey questions. For RQ2, participants were directly asked during interviews which SIVs were most helpful, and responses were analyzed to quantify favorable mentions by name. For comparison, each conventional-plus technology was assigned a binary category of complexity. “Complex” technologies were those with many interconnected parts, intricate assemblies, and complicated functions, such as the mini-split system, fiber optics, and condensing storage water heaters. “Simple” technologies were those with fewer assemblies and operating parts, such as triple-pane windows and laminated vinyl tile.

Results

Eight of the closed-ended survey questions were dedicated to understanding whether students felt that the SIVs had any impact on their performance and the quality of their learning experience (QoE) in terms of utility (RQ1). Across all students, 95.3% (n=33) ‘agreed’ or ‘strongly agreed’ that the SIVs made unfamiliar construction topics in the readings easier to understand (Figure 1). In an open response follow-up question, one participant explained that the SIVs “gave a visual background to the technology, that for me, were totally new topics. By having the images narrated, it gave a deeper understanding than view[ing] textbook pictures.” Another wrote that the SIVs “[provided] a clear and concise introduction to a topic with visuals, [which] helped before getting into greater detail.” About three-quarters of the students, 71.5% (n=30), ‘disagreed’ or ‘strongly disagreed’ that watching a video made them less likely to do the assigned readings, while 81% (n=34) felt like the videos made the assigned reading go faster. Students were most divided on whether they believed the videos helped them with their graded assignments. Agreement and disagreement were equal, totaling 35.7% (n=15) each, with the remaining 28.6% (n=12) indicating that they ‘neither agree nor disagree.’ Interview data suggest that the near-normal distribution of responses to this question may be attributable to the determination of some students to perform to a certain standard regardless of the demands on their effort. One participant’s response best exemplifies this sentiment:

> I don't know how much [the SIVs] really helped my quiz grade, to be honest. But like I said, I feel like I genuinely learn more by watching them…instead of reading 10 pages of PDF and still being semi-confused…. I don't know if it helped my grade, but it made me learn [the material] instead of just read[ing] it.

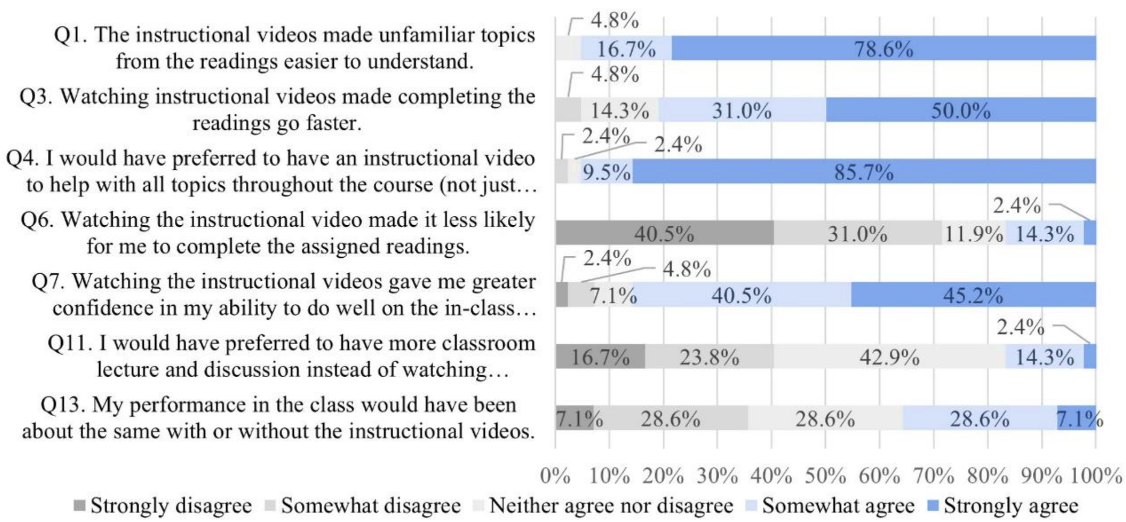


Figure 1. Student perceptions of the impacts of SIVs on their performance.

When asked what, if any, recommendations they had for the use of instructional videos in the course, participants frequently responded that SIVs should be provided for all topics, not just half of them. In many cases, students stated that they wanted to see SIVs used in their other courses as well. Encapsulating this viewpoint, one student said:

> Honestly,...sometimes I feel like, in a lot of classes I'm taking, [teachers] assume I know exactly what [they're] talking about. [T]hey...use terms that I actually haven't heard before...[and] I end up trying to look them up [during the discussion]. So, I think, [the SIVs] give a quick basis of what we're talking about before going into readings and...class discussions. I think that [the SIVs] really helped.

Only 16.7% (n=7) either 'agreed' or 'strongly agreed' that they would have preferred to have more classroom lecture and discussion instead of watching instructional videos, suggesting that students were generally satisfied with the balance of video- and lecture-based learning in the course.

RQ2 focused on which SIVs were most helpful for students. In general, the topics with more complex technologies received the most mentions during interviews, while the simple technologies were mentioned less frequently or not at all (Table 1). Students provided additional support for this relationship between topic complexity and the value of SIVs. One participant offered his recommendation of when SIVs should be used: "Include the [SIVs] as much as possible, [but] I don't think it's necessary for everything. I think [they] should only be used for the more complicated technologies." Another student, while discussing condensing storage water heaters, explained why more complex topics are conducive to video supplementation. He said,

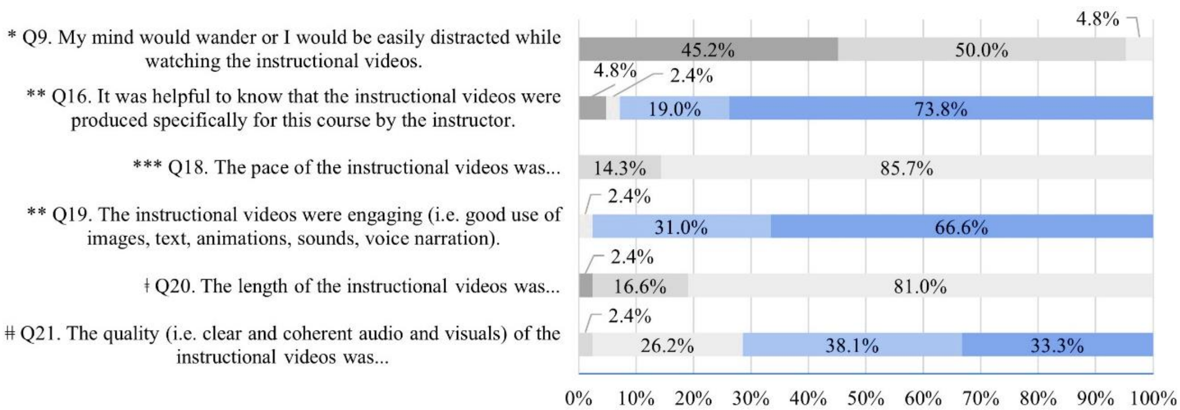
> "Before I just thought it was a big tub of water... I didn't really know how it worked at all. And it's a pretty complex system. So, seeing that visual and actually going through the process of how [water] actually goes through the coils and everything. I didn't know any of that was in there."

This trend has exceptions. While solar shingles used in roofing would normally be considered a more complex topic than premium sheathing systems used in wall framing, more students mentioned the SIV for premium wall sheathing than the SIV for solar shingles.

Table 1. Frequencies of mentions of each conventional-plus topic in the interviews.

Technology	Topic Complexity	# Students who received the SIV	# of Topic mentions	% of Topic mentions
Mini-split system	Complex	21	8	38%
Condensing storage water heater	Complex	24	5	21%
Fiber optics	Complex	25	5	20%
Closed crawl space	Complex	21	4	19%
Premium sheathing	Simple	21	4	19%
Insulated vinyl siding	Simple	21	2	10%
Solar shingles	Complex	22	2	9%
Premium subfloors	Simple	25	1	4%
Trusses	Simple	22	0	0%
Triple-pane windows	Simple	25	0	0%
Radiant barrier	Simple	24	0	0%
Laminated vinyl tile	Simple	25	0	0%

The final research question (RQ3) focused on student perceptions of the design and development of the SIVs and how they impact their QoE through viewing ease and enjoyability. Overwhelmingly, 97.6% (n=41) of students reported in the survey that they 'strongly agree' or 'somewhat agree' that the videos were engaging, making good use of images, text, animations, sounds, and voice narration. Three survey questions asked about the pace, duration, and quality of the videos. 85.7% (n=36) of the class reported the pace of the SIVs was ‘about right’. The remaining 14.3% (n=6) of respondents thought the videos were ‘too slow.’ 81.0% (n=34) of the class reported that the roughly 3-minute duration of the videos was ‘about right’. One student explained in an interview that “even though [the SIVs are] only three and a half minutes, they definitely convey a lot of information that you can retain easily through the graphics and the sounds.” The remaining 19.0% (n=8) of students, nearly a fifth of the class, felt that the videos were either ‘too short’ or ‘far too short.’ During the interviews, one student said that “around 10-to-12 minute length [for the SIVs] would really be good.” 33.3% (n=14) of the class thought the quality of the SIVs in terms of audio and visuals was ‘excellent,’ while 38.1% (n=16) thought the quality was ‘above average,’ and 26.2% (n=11) thought the quality was ‘average.’ One person (2.4%) thought the quality was ‘below average.’



Scales Key:
* Never, Rarely, Sometimes, Often, Always
** Strongly disagree, Somewhat disagree, Neither agree nor disagree, Somewhat agree, Strongly agree
*** Far too slow, Too Slow, About right, Too fast, Far too fast
ǂ Far too short, Too short, About right, Too long, Far too long
ǂǂ Very poor, Below average, Average, Above average, Excellent

Figure 2. Student perceptions about the SIVs’ design.

Discussion

This paper began with three research questions, each focused on how to improve CM students’ QoE. The first (RQ1) asked if watching a SIV before completing assigned readings improved understanding of the topic. Participants of the study reported affirmatively, echoing the findings of Hoxley & Rowsell (2006), Cherrett et al. (2009), and Liu & Hatipkarasulu (2014) who found that instructional videos had a positive impact on student understanding of course content. However, surprisingly, in a follow-up question in which the participants were asked whether they believed that the SIVs had any measurable impact on their performance in terms of grades, they were starkly divided. Over a third of the class felt that the SIVs boosted their grades. The same number were skeptical, expressing uncertainty as to whether the SIVs made any real difference. The mixed findings in the literature and this research study have a few possible explanations. First, improvements in understanding may not directly correlate with better performance on quizzes. The quizzes asked precise questions with limited answer options, potentially making students reluctant to claim that their specific understanding of each reading was adequately reflected in those questions. Alternately, for some students, improved understanding may be a more distant precursor to perceived improvements in quiz performance. Without many previous opportunities to demonstrate their understanding of the unfamiliar topics, students may still feel unsure about what they know and hesitant to claim any improvement on class assignments. Future research might change or broaden the testing instrument to give study participants more opportunities to openly express their understanding with greater confidence. Other explanations point to the uncontrolled variability in student effort. This study was conducted in a real-world setting in which the participants were responsible for self-administering the SIVs in their own environments, at their convenience, and on their own devices. In the weeks that students did not receive a SIV, they could have compensated with additional time and effort with the readings. Future research might attempt to remove these variables (e.g., study time, viewing devices, and environmental distractions) by conducting the study in a highly controlled lab setting in which the SIVs are administered by the researchers directly. Another consideration is that, in accordance with guidelines described in the literature, the SIVs were intentionally designed to be short. On average the videos were just under three minutes long. While most of the students believed this was sufficient, a few disagreed. Future work should consider amplifying the impact of SIVs by using longer videos to see how it impacts understanding, performance, and QoE. The second research question (RQ2) asked participants which SIVs helped them the most. In general, the complex topics were named more frequently, which is the same result that Liu & Hatipkarasulu (2014) reported. The final research question (RQ3) asked about the design of the SIVs. The results of this study were similar to Wong et al. (2018), in that participants were overall pleased with the design of the SIVs in terms of pace, duration, engagement, and quality.

Conclusion

Video has become the preferred medium of learning for the current college-age generation. This paper presented the findings of a mixed-method study exploring the impact that SIVs have on CM students' quality of the learning experience (QoE), their understanding, the value of SIVs for different course topics, and the quality of SIVs designed in accordance with current guidelines. Insights from both surveys and interviews clearly indicate that well-designed SIVs have a substantial, positive impact on the QoE and are the most helpful with relatively complex subjects. Overall, these results add to the growing body of knowledge by providing CM teachers with an evidence-based way to update or augment their existing curriculums without extensive changes. In consultation with the latest literature on video design, instructors can build or select SIVs for their courses and apply them strategically to their most challenging topics.

References

Barnes, A. F. (2021). Instructional Video Object-Based Learning in a Flipped Construction Management Classroom (Doctoral dissertation, Virginia Tech).

Bernold, L. E. (2005). Paradigm Shift in Construction Education is Vital for the Future of Our Profession. Journal of Construction Engineering and Management, 131(5), 533–539. https://doi.org/10.1061/(ASCE)0733-9364(2005)131:5(533)

Chan, Y. M. (2010). Video instructions as support for beyond classroom learning. Procedia - Social and Behavioral Sciences, 9, 1313–1318. https://doi.org/10.1016/j.sbspro.2010.12.326

Cherrett, T., Wills, G., Price, J., Maynard, S., & Dror, I. E. (2009). Making training more cognitively effective: Making videos interactive. British Journal of Educational Technology, 40(6), 1124–1134. https://doi.org/10.1111/j.1467-8535.2009.00985.x

Hoxley, M., & Rowsell, R. (2006). Using Video in the Construction Technology Classroom: Encouraging Active Learning. Architectural Engineering and Design Management, 2(1–2), 115–122. https://doi.org/10.1080/17452007.2006.9684609

Kay, R. H. (2012). Exploring the use of video podcasts in education: A comprehensive review of the literature. Computers in Human Behavior, 28(3), 820–831. https://doi.org/10.1016/j.chb.2012.01.011

Kay, R. H. (2014). Developing a Framework for Creating Effective Instructional Video Podcasts. 9(1), 10. https://pdfs.semanticscholar.org/9bcc/94d61ae0c25e2924569222cda1b5f23b8f50.pdf

Le Callet, P., Moller, S., & Perkis, A. (2012). Qualinet white paper on definitions of quality of experience. Retrieved from http://www.qualinet.eu/images/stories/whitepaper v1. 1 dagstuhl output corrected.pdf

Liu, R., & Hatipkarasulu, Y. (2014). Introducing Building Information Modeling Course into a Newly Developed Construction Program with Various Student Backgrounds. 8.

Ljubojevic, M., Vaskovic, V., Stankovic, S., & Vaskovic, J. (2014). Using supplementary video in multimedia instruction as a teaching tool to increase efficiency of learning and quality of experience. The International Review of Research in Open and Distributed Learning, 15(3). https://doi.org/10.19173/irrodl.v15i3.1825

McGarr, O. (2009). A review of podcasting in higher education: Its influence on the traditional lecture. Australasian Journal of Educational Technology, 25(3). https://doi.org/10.14742/ajet.1136

Pearson Education, New Research Finds YouTube, Video Drives Generation Z Learning Preference. (2018). Retrieved February 22, 2020, from https://www.pearson.com/content/dam/one-dot-com/one-dot-com/global/Files/news/news-annoucements/2018/The-Next-Generation-of-Learners_final.pdf

Wiley, D., (2002). The instructional use of learning objects (1st ed). Bloomington, Ind: Agency for Instructional Technology: Association for Educational Communications & Technology. https://members.aect.org/publications/InstructionalUseofLearningObjects.pdf

Wong, J. K. W., Oladinrin, O. T., Ho, C. M. F., Guilbert, E., & Kam, R. (2018). Assessment of video-based e-learning in a construction measurement course. International Journal of Construction Management, 1–7. https://doi.org/10.1080/15623599.2018.1435152

Zaneldin, E., Ahmed, W., & El-Ariss, B. (2019). Video-based e-learning for an undergraduate engineering course. E-Learning and Digital Media, 16(6), 475–496. https://doi.org/10.1177/2042753019870938

Evaluating the Effectiveness of Building Information Modeling (BIM) and Virtual Reality (VR) in Understanding Mechanical, Electrical, and Plumbing (MEP) Plans

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The application of Building Information Modeling (BIM) and Virtual Reality (VR) has been explored within the context of the Architectural Engineering and Construction (AEC) industry to enhance visualization and communication among stakeholders. VR applications have extended into the AEC educational environment as a learning tool to aid students in better visualizing and understanding the project. This was done to mitigate the shortcomings of traditional 2D plans that are not as readily understood. The existing literature indicates that teaching Mechanical, Electrical, and Plumbing (MEP) plan reading with BIM/VR support has been explored minimally and qualitatively. The authors of this paper aim to fill this gap and present a quantitative study of BIM/VR applications in assisting MEP plan reading. In this study, the participants who are sophomore level students with minimal experience with BIM/VR and MEP systems were split into control and test groups, respectively. The effectiveness of learning was assessed statistically through pre-training and post-training quizzes. Furthermore, both groups were asked to complete a Likert scale questionnaire to evaluate their attitudes toward BIM/VR applications at the end of the study. The results show that BIM/VR integration significantly improved the performance of students.

Key Words: Mechanical, Electrical, and Plumbing; Building Information Modeling; Virtual Reality; Plan Reading.

Introduction

Plan reading is a critical skill and component of the Architecture, Engineering, and Construction (AEC) industry, as this is how essential information, details, and project scope are communicated amongst all parties involved in a project. Despite plan reading being a critical skill, many young AEC professionals fall behind in plan reading interpretation (Ghanem, 2022; Lee & Hollar, 2013). This is due to traditional 2D plans being limited in the extent of information they can provide. More specifically, they are disadvantaged in the visualization aspect and provide fragmented elements of the project such as views, sections, and elevations. Therefore, there is often misinterpretation of information and in many cases, this leads to financial and time losses (J. Wang et al., 2014). Mechanical, Electrical, and Plumbing systems are not excluded from those limitations, and in some cases are severely impacted due to their overly complex and intricate nature (Dallasega et al., 2021; Khanzode et al., 2008).

As a solution to the shortcomings of standard 2D plans, the integration of Building Information Modeling (BIM) along with Extended Reality (XR) applications has exponentially grown over the years (Ghanem, 2022; Gu & London, 2010; Mohamudally, 2018). Yet, this growth did not fully encompass the MEP systems, despite the fact that they can account for about 40% - 60% of the project cost and labor (Dallasega et al., 2021; Khanzode et al., 2008). The benefits of incorporating BIM/VR into a construction project can be extended into the MEP systems portion of the project as well. Therefore, the advantages of BIM/VR applications within MEP systems need to be evaluated and further explored.

BIM-VR Application in the AEC Education Environment

The combination of BIM/VR within the curriculum of AEC classes has been investigated, and the benefits were studied by a few researchers (Na et al., 2022). Amongst those who investigated it, most depended on student feedback through interviews and surveys (Alizadehsalehi et al., 2021; Wong et al., 2020). However, very few attempted to quantify the benefits of BIM/VR within the education context. Many researchers suggested a comprehensive framework of how the integration of BIM/VR can be adopted into the classroom (Ghanem, 2022; C. Wang et al., 2018).

A case study was developed in an attempt to assess the applicability and effectiveness of BIM/VR incorporation into the classroom (Alizadehsalehi et al., 2021). The authors developed a course that targeted the application of BIM/VR with 23 students as the participants. The students deemed motivation as the highlight of their experience, indicating that BIM/VR increased their enthusiasm to learn. Visualization, creativity, and interaction followed as the highlight of the experience (Alizadehsalehi et al., 2021). Another study introduced a framework for BIM/VR applications' integration in the classroom (Wong et al., 2020). Then, at the end of the study, a questionnaire was administered to evaluate the opinions toward BIM/VR incorporation into the classroom with a total of 57 participants. The analysis of the responses yielded that the students had positive attitudes toward the new learning experience with increasing enthusiasm to learn (Wong et al., 2020).

BIM-VR Application in MEP Systems

The incorporation of BIM/VR applications in both the AEC industry and education environment was focused on the architectural and structural elements of a project. However, there are limited applications of BIM/VR incorporation within the context of MEP. Among the limited number of related works of literature, most adopted a qualitative approach of surveys and questionnaires (Khanzode et al., 2008). The benefits of BIM/VR to aid in the interpretation of MEP systems are an extension of the general benefits provided by BIM/VR applications in the AEC industry and education environment. Some examples of said benefits include the reduction of RFIs, MEP coordination, and change orders. This produces more accurate as-built models allowing for easier facility management, significant reductions in cost and time, and fewer conflicts amongst all parties. This is due to efficient communication and collaboration of information (Khanzode et al., 2008).

In a case study attempting to evaluate the effectiveness of BIM/AR within the context of MEP systems, industry professionals were interviewed to evaluate the potential applications and benefits (Dallasega et al., 2021). Significant time reductions for the completion of several tasks were reported compared to the traditional methods. Also, measurement accuracy increased, especially for areas with high-complexity (Dallasega et al., 2021). Another case study quantitatively investigated the aspect of design in MEP systems, and the application of BIM/VR by statistically analyzing the pre and post-test scores of a control and test group (Espinoza et al., 2021). The study proved that BIM/VR enhanced the learning experience and increased the students' understanding of MEP systems. However, this case study did not extend to the aspects of building construction, such as interpreting MEP drawings, generating quantity take-off, performing clash detection, etc.

Problem Statement

MEP systems are complex and major components of construction projects. Due to these intricate systems existing within limited spaces, they are usually faced with many errors, clashes, and inaccurate estimates. This negatively impacts the construction process as it increases the time cost required to complete a project. Therefore, the application of BIM/VR can aid in interpreting and visualizing MEP components and systems. Yet, there is limited research exploring the full effect of BIM/VR combined application within MEP systems and its ability to enhance MEP plan reading skills. This case study aims to quantitatively evaluate the effectiveness of BIM/VR applications within the scope of MEP systems to test if it will increase the efficiency and accuracy of MEP plan reading. The study also aims to provide a method of enabling young AEC professionals to enhance their understanding of MEP systems with little experience in construction processes. Therefore, covering the gap where MEP systems have been minimally explored where both BIM/VR were applied simultaneously. Thus, a quantitative dataset provides insightful information within the AEC industry and education environment.

Research Approach

The study followed a general workflow as detailed in Figure 1, which consisted of conducting a literature review on the topic to systematically summarize the state of current research within the field. Then, a set of plans for a commercial building was selected for the purpose of the study. The plans were converted to a 3D/VR model. Next, the participants of the study were identified. The evaluation method of the effectiveness of BIM-VR assisting in MEP systems plan reading was developed. Finally, the results of the study were statistically analyzed, and its findings were reported.

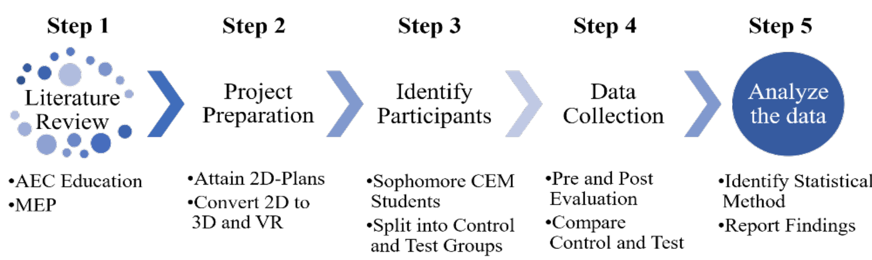


Figure 1. General workflow

Step 1: Literature review. The study's literature review focused on the application of BIM/VR within the scope of the AEC classroom. Next, BIM/VR applications within MEP systems in literature were highlighted. In each category, the research, approach, results whether results were qualitative or quantitative, and findings were studied and reported.

Step 2: Project Preparation. Next, the 2D plans of a retail facility (Goodwill Industries) were chosen as the base of evaluation. The plans were then converted into a detailed 3D model using Autodesk Revit 2022. The MEP components of the model were developed to match those in the plans as accurately as possible in specification, sizes, and dimensions. Then, using the Enscape plugin in Autodesk Revit, the model was exported to a VR-friendly platform. Next, using the Oculus Quest 2 VR goggles, the 3D model was VR accessible. Figure 2 illustrates the process taken, along with the software and equipment used to create the BIM/VR model.

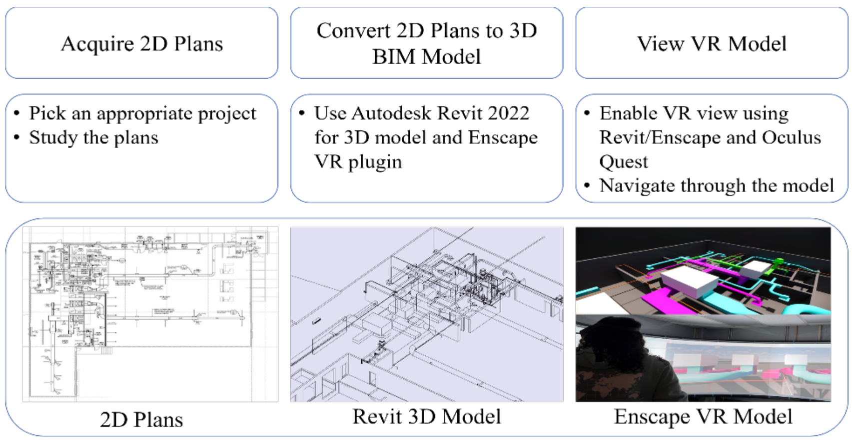


Figure 2. 2D to 3D/VR model process

Step 3: Identify Participants. The participants of the study were identified as students of a sophomore-level CAD course within the XXX curriculum at the XXX. The evaluation was conducted at the beginning of the semester, ensuring that all students have little or no experience with BIM/VR, as well as MEP systems. The students were sectioned into a control group (11 students) and a test group (10 students) to fully evaluate the effectiveness of BIM/VR applications within MEP systems. The control group was asked to complete the tasks of MEP systems plan reading using only the 2D plans while the test group had access to both the 3D and VR models during the evaluation process.

Step 4: Data Collection. The evaluation process was completed over the course of two weeks. This ensured the elimination of a possible learning curve that can affect the results of the study. The evaluation consisted of a pre-quiz and a post-quiz in both the control and test groups (Figure 3). The questions for both groups were identical in both quizzes and covered general topics such as element identification, dimension, quantity take-off, and clash detection. The clash detection question asked students to identify components of the project where there was a clear violation of space constraints, in which two elements occupied the same space. The same parameters for clash detection were applied in both pre-and-post-quiz phases. The major difference is that the test group had access to the BIM/VR models during the post-quiz phase while the control group had access after the completion of both quizzes. Also, the control group was given a set of 2D plans that were generated from the 3D Revit model for the clash detection portion. This was to ensure that both groups had matching locations of clashes to allow for the evaluation of clash detection using 2D plans vs 3D/VR. Both quizzes consisted of a total of seven questions as further elaborated in Figure 3, and students were given 45 minutes to complete them. The pre-quiz was administered under identical conditions for both groups with access to only the 2D plans. The aim of the pre-quiz was to evaluate both the control and test group under identical conditions of no BIM or VR access. Then, both groups had a training session on MEP plan reading with the added topic of BIM/VR for the test group before taking the post-quiz. During the post-quiz, the control group had access to only the 2D plans while the test group was granted access to the 3D and VR models. This is aimed at evaluating the difference in the performance of both groups to identify if BIM/VR had a significant positive impact on learning how to interpret and understand MEP systems. After completion of the post-quiz, the control group was given access to both the 3D and VR models, then both groups were asked to complete a Likert-scale questionnaire on their perceptions of BIM/VR application for MEP plan reading. The entire process of quizzes and questionnaire were administered online through the university's platform as a multiple-choice quiz. The quizzes were completed during the class time while the questionnaire was completed at the end of the training outside of class time.

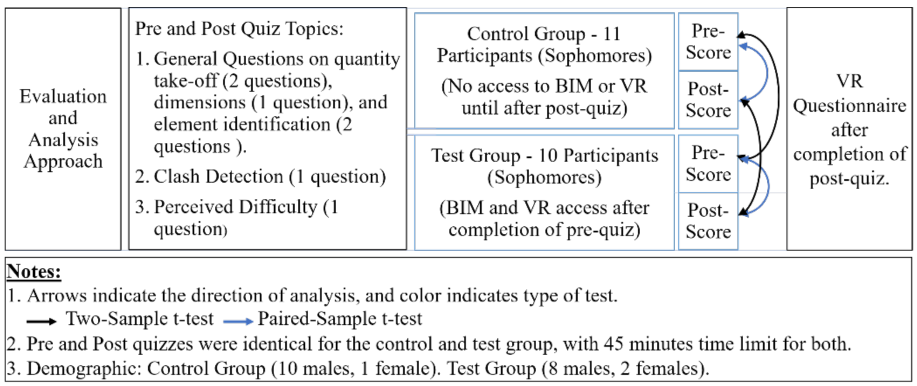
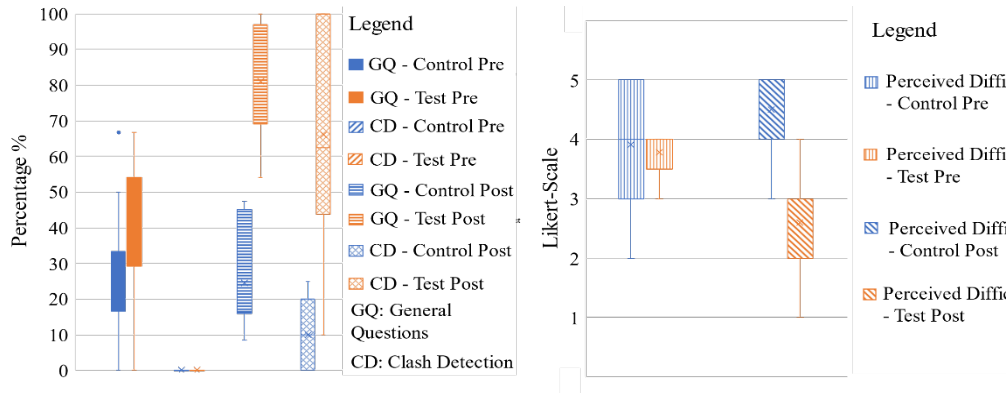


Figure 3. Evaluation and analysis approach

Step 5: Analyze the Data. Finally, the results of the experiment were analyzed using several statistical methods of a two-sample t-test, paired-sample t-test, and correlation coefficients. Figure 3 illustrates a graphical simplification of the evaluation and analysis approach. First, the pre-scores were analyzed across the control and test group on the general questions, clash detection, and perceived difficulty of the questions on the quiz to evaluate if any significant changes occurred. This was repeated for the post-scores results. Then, each group's results were analyzed separately from pre-to-post-scores. This was to study the impact BIM/VR applications had on the learning experience of MEP systems. Finally, the results of the questionnaire were evaluated to gauge the students' interest and attitude toward VR application for MEP system interpretation.

Results and Discussion

The results were clustered into three main categories: the analysis of the pre-to-post scores of the general questions, clash detection abilities, and perceived difficulty of the quiz questions. This was done across the control and test groups. Then, analysis was done for both the control and test group separately to further explore the significance of BIM-VR integration into the education environment of AEC. The statistical results are highlighted in Figure 4. A scale of 0 to 100 was utilized for general questions and clash detection portions and a scale of 1 to 5 for perceived difficulty. A score of 0 indicates significantly low performance for the quiz and clash detection portion, while a score of 1 implies that the students found the process to be extremely easy under the perceived difficulty category. On the other hand, a score of 100 would indicate a perfect score for the first two categories and a score of 5 indicates an extremely difficult process under the perceived difficulty portion.



(a) General Questions and Clash Detection (b) Perceived Difficulty

Figure 4. Statistical results

The control and test groups were tested comparatively to each other validating the importance of BIM/VR application in the classroom (Table 1 and Figure 4). First, the general questions portion, clash detection, and perceived difficulty scores were compared for the pre-phase. The t-test p-values were not significant for all, thus indicating that both groups performed similarly when both groups had no BIM/VR access. Next, when comparing the post results of the same categories, we see a significant increase in the test group's scores compared to the control group. Therefore, supporting the hypothesis that BIM/VR integration in the AEC classroom has a substantial positive impact on improving the students' interpretation of MEP plans and concepts such as clash detection, quantity take-off, dimensioning, etc. The correlation coefficient was also produced from the post-phase comparing the control and test groups as shown in Figure 5. A 0 on the x-axis means students had no access to BIM/VR (control group) and 1 indicates access to BIM/VR (test group). Also, correlation coefficients range from 0 to 1, with 0 being no correlation, and 1 indicating a strong correlation. Hence, there is a substantial correlation between score improvement for both the general questions and clash detection portions with values of 0.8907 and 0.7705 when BIM was used. As for perceived difficulty, there is a strong negative correlation (-0.7889), indicating that the test group utilizing BIM/VR viewed the quiz to be much easier than the control group that did not have BIM/VR access.

Table 1

Paired and two sample t-test and results

Item	P-value (Prob > t)	P-value (Prob > t)	P-value (Prob > |t|)
	Quiz Score	**Clash Detection**	**Perceived Difficulty**
Test vs Control Group (Pre to Pre)	0.0871	-	0.6877
Test vs Control Group (Post to Post)	<0.0001*	0.0002*	<0.0001*
Control Group (Pre to Post)	0.6254	0.0034*	0.0248*
Test Group (Pre to Post)	0.0002*	<0.0001*	0.0023*

*Significant

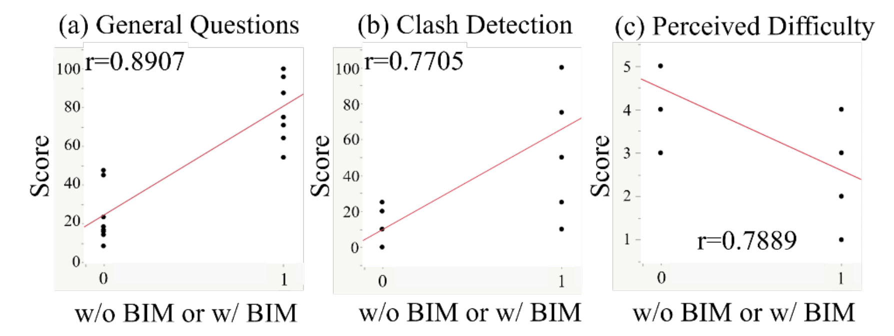


Figure 5. Correlation coefficients (control vs test post-phase)

Moving on, when inspecting the t-test p-values for the control group as shown in Table 1, they showed no significant change in scores for the general questions portion from pre-phase to post-phase. This is also illustrated in Figure 4. The score in pre-phase and post-phase is 27.3% and 24.5% respectively, which are very close to each other. However, the score seemed to show some increase in the clash detection portion after the orientation. This was due to students' lack of knowledge of what clash detection represented before participating in the training session. Therefore, students were unable to answer that portion correctly in the pre-quiz phase. This explains the 10% score increase in clash detection ability for the control group as they were able to at least try and identify possible clashes using the provided 2D plan set generated from the 3D Revit model. Yet, this is still well below the acceptable level of clash detection comprehension and identification. Also, the perceived difficulty has significantly increased from 78% to 90% despite the previously mentioned training session aimed at familiarizing the students with MEP plans (Figure 4). It can be concluded that the control group's performance in MEP system interpretation was not improved within the short training period when the only access to 2D plans of MEP systems was provided. Furthermore, there is a trend of a considerable amount of variability in scores for both the pre and post-general questions portion (Figure 4). As for the case of the post scores of clash detection, it appears that the scores were centered towards the lower end of the plot with some variability (Figure 4).

Next, the same steps of analysis followed for the control group were applied to the test group (Table 1 and Figure 4). The mean of scores significantly increased from 40% to 81% for pre-vs-post-scores for the general questions portion. A significant improvement in clash detection was observed where the scores increased from an average of 0% in the pre-quiz phase to a 66% in the post-quiz phase. Finally, the perceived difficulty associated with completing the quiz significantly decreased from 75.6% to 52.0%. Those results indicate that when students were given access to BIM/VR to aid in the interpretation of MEP plans, their performance significantly improved compared to when they did not have access to said resources. Also, the variability in the scores for the test group decreased in the post-phase of the general questions portion compared to the pre-phase. As for clash detection, the test group's clash detection post-scores were considerably variable. This can indicate that the comprehension of the concept of clash detection improved for some students while others still needed more training or more time to familiarize themselves with the mechanism of identifying clashing elements.

Finally, the results of the Likert-scale questionnaire were evaluated as presented in Figure 6. The questionnaire included questions investigating students' familiarity with VR applications, and the various ways it helped them with the application of MEP systems. The questions included topics such as enhanced motivation, visualization, comprehension, clash detection ease, and status of the learning experience. Both the control and test groups were asked to complete the questionnaire, and according to the results, the students had positive feedback on their experience with using BIM/VR to interpret and read MEP plans. The average response was almost above 4 for all questions, except the previous experience with VR which scored below 3. The students seemed to value the visualization and clash detection aspects of BIM/VR the most, as they had the highest average approval response of 4.8 and 4.7, respectively compared to the total average of 4.4 out of 5.0.

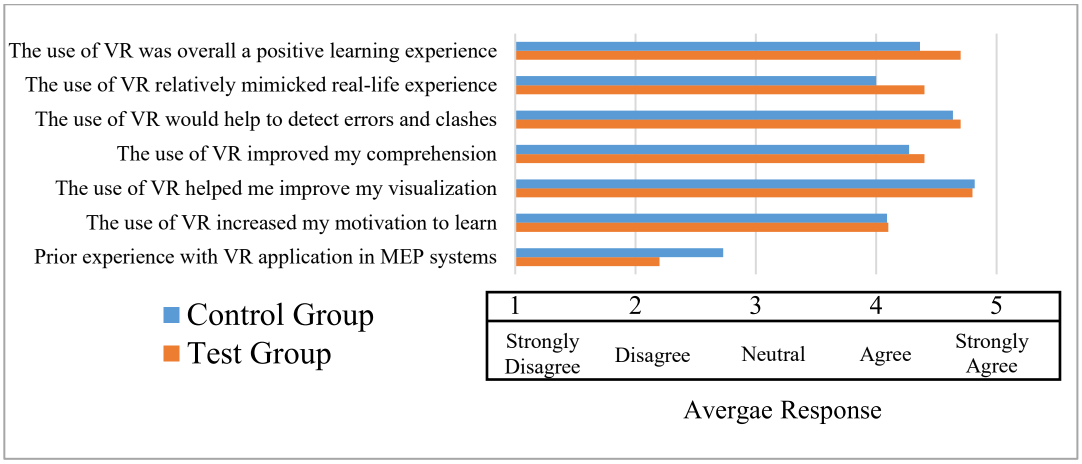


Figure 6. Questionnaire results

Conclusion

The results confirmed that the integration of BIM/VR is significantly beneficial to students' performance when interpreting MEP plans. First, the score average was considerably higher when comparing the control group to the test group in the post-quiz phase. Next, there was a significant increase in the test group's performance when comparing the pre-to-post scores. Furthermore, there is a similar trend when it comes to analyzing the students' ability to complete clash detection tasks where the test group performed much better compared to the control group during the post-phase, and there was a significant increase in their post-scores compared to the pre-scores. As for the perceived difficulty portion, there is an increase for the control group from the pre-to-post phase, where they seem to have not felt an improvement in their ability to answer the question with only 2D plans. Yet, there is a significant decrease in perceived difficulty for the test group from when they only had access to the 2D plan (pre-quiz) to when they had access to both BIM/VR (post-quiz). Furthermore, according to the questionnaire results, the students had very positive attitudes toward the application of BIM/VR. Therefore, this study concludes that the incorporation of BIM/VR into the AEC classroom enhanced the interpretation of MEP plans and systems. The study was conducted on an accelerated schedule of two weeks. The absence of a learning curve on the ability to better read 2D plans, it was proved that BIM/VR applications in education can scientifically improve and accelerate comprehension of MEP systems. In future studies, this experiment can be conducted in a MEP class over the duration of a semester. This would allow the students more extensive training on 2D plan reading for MEP systems, thus further evaluating the benefit of BIM/VR incorporation into the classroom.

References

Alizadehsalehi, S., Hadavi, A., & Huang, J. C. (2021). Assessment of AEC Students' Performance Using BIM-into-VR. *Applied Sciences*, *11*(7), Article 7. https://doi.org/10.3390/app11073225

Dallasega, P., Schulze, F., Revolti, A., & Martinelli, M. (2021). Augmented Reality to increase efficiency of MEP construction: A case study. *ISARC Proceedings*, 459–466.

Espinoza, V. P. R., Cardenas-Salas, D., Cabrera, A., & Coronel, L. (2021). Virtual Reality and BIM Methodology as Teaching- Learning Improvement Tools for Sanitary Engineering Courses. *International Journal of Emerging Technologies in Learning (IJET)*, *16*(06), Article 06. https://doi.org/10.3991/ijet.v16i06.13535

Ghanem, S. Y. (2022). Implementing virtual reality—Building information modeling in the construction management curriculum. *Journal of Information Technology in Construction (ITcon)*, *27*(3), 48–69. https://doi.org/10.36680/j.itcon.2022.003

Gu, N., & London, K. (2010). Understanding and facilitating BIM adoption in the AEC industry. *Automation in Construction*, *19*(8), 988–999. https://doi.org/10.1016/j.autcon.2010.09.002

Khanzode, A., Fischer, D. M., & Reed, D. (2008). Benefits and lessons learned of implementing building virtual design and construction (VDC) technologies for coordination of mechanical, electrical, and plumbing (MEP) systems on a large healthcare project. *Journal of Information Technology in Construction (ITcon)*, *13*(22), 324–342.

Lee, N., & Hollar, D. A. (2013). Probing BIM Education in Construction Engineering and Management Programs Using Industry Perceptions. *49th ASC Annual International Conference Proceedings*. ASC Annual International Conference, San Luis Obispo, California.

Mohamudally, N. (2018). *State of the Art Virtual Reality and Augmented Reality Knowhow*. BoD – Books on Demand.

Na, R., Aljagoub, D., & Webber, R. (2022). Integrating Virtual Reality (VR) Into Construction Engineering and Management (CEM) Courses-A Case Study. *EPiC Series in Built Environment*, *3*, 633–642. https://doi.org/10.29007/4lpt

Wang, C., Li, H., & Kho, S. Y. (2018). VR-embedded BIM immersive system for QS engineering education. *Computer Applications in Engineering Education*, *26*(3), 626–641. https://doi.org/10.1002/cae.21915

Wang, J., Wang, X., Shou, W., & Xu, B. (2014). Integrating BIM and augmented reality for interactive architectural visualisation. *Construction Innovation*, *14*(4), 453–476. https://doi.org/10.1108/CI-03-2014-0019

Wong, J.-Y., Yip, C.-C., Yong, S.-T., Chan, A., Kok, S.-T., Lau, T.-L., Ali, M. T., & Gouda, E. (2020). BIM-VR Framework for Building Information Modelling in Engineering Education. *International Journal of Interactive Mobile Technologies (IJIM)*, *14*(06), Article 06. https://doi.org/10.3991/ijim.v14i06.13397

SUBMISSION: 58
TITLE: Evaluating the Effectiveness of Building Information Modeling (BIM) and Virtual Reality (VR) in Understanding Mechanical, Electrical, and Plumbing (MEP) Plans

Thank you to all of the reviewers and editorial staff for taking the time to help us improve the quality of our work. Here highlighted are some changes and responses to some of the comments provided.

The changes made according to reviewer 1 were further elaboration on the data acquisition process under Research Approach Step 4. The authors would like to point out that while the questions were not published as they might be reused for a future repeat of the study, Figure 3 details the type of questions asked and number of questions per concept. Also, the study detailed that in the pre-phase of the process, students lacks experience on all fronts from plan reading to BIM/VR. The purpose was to study the benefit of BIM/VR under circumstances of minimal experience and how it can improve comprehension. Then, both groups were giving a training session on respective topics as appropriate per group for the post-phase evaluation. In that session concepts of plan reading were discussed and brief explanation of how to read 2D plans was given. As for the test group, Revit was introduced and interface explained to be able to use during the post-quiz. This was explained under step 4 as well.

Moving on, the comments of reviewer 2 were addressed as follows; abbreviations were checked and an explanation was provided on first appearance, the term blueprint was replaced with the more appropriate plans, and the scale for perceived difficulty was updated to its original 1 (very easy) to 5 (very difficult) Likert scale. The difficulty question was originally asked on a Likert-scale to evaluate how difficult the participants perceived the process, it was changed to 0 to 100 for consistency, but since authors agreed that it might be confusing or inappropriate, thus it was updated. Also, demographics of gender were not originally added since no analysis was done across gender but has been added under Figure 3 for clarification. As for level of knowledge, that was previously mentioned in Research Approach Step 3, Figure 3, and Figure 6, and has also now been elaborated on in the abstract. Figure 4 has been updated to make it easier to read and understand and to keep consistent with Figure 5. As for the last comment, further elaboration was added to the conclusion where the improvement was attributed to enhanced visualization and spatial recognition as concluded from Figures 4, 5, and 6, as well as Table 1. Furthermore, as pointed out the study was completed over a short two-weeks period, as to eliminate possible learning curves to better analyze the benefit of BIM/VR vs 2D.

Finally, for the comments of reviewer 3, the sample size is limited by the number of students in the program, and since our program is a small one of no more than 20-30 per session, this is a limitation of the study.

Effective Use of a Digital Demonstrator for the Instruction of Laser Scanning

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Atlanta, Georgia

This research contributes to the understanding of digital demonstrators as a tool for classroom instruction in the use of laser scanners. Laser scanning technology plays an essential role in construction management. At the university level, students in this domain must demonstrate theoretical knowledge through hands-on exposure to laser scanning technology. Obtaining laser scanners requires a substantial capital investment as well as ongoing maintenance costs. This impedes the ability of many institutions to provide scanners for classroom use, resulting in a scarcity of such equipment and posing an instructional challenge. Use of digital demonstrators offers the potential to augment or replace a physical laser scanner in the classroom. For this study, researchers examined the current method of scanner instruction and developed a simulated scanner which functions as a digital demonstrator. The use of the demonstrator was subjected to mixed methods analysis using both undergraduate and graduate student subjects at the Georgia Institute of Technology. Testing concluded that integrating the digital demonstrator in the instruction workflow enhanced student learning and enabled those who used it to rapidly adapt to a physical scanner. The paper finally offers suggestions for further research including wider testing and examination of broader applications within STEM instruction.

Key Words: Digital demonstrator, Laser scanning, Construction education.

Introduction

Laser Scanners are widely used in the construction industry to capture details of existing structures and objects. Laser scanners analyze the built environment, including real-world objects, by collecting data on shape and appearance. The resulting data is frequently applied to develop digital three-dimensional models. (Ebrahim, 2015). Laser scanners use laser beams to create a three-dimensional point cloud. The scanner sends out a laser beam and calculates resulting point cloud information based on the amount of time taken by the beam to return to the scanner. These point clouds can then be used to derive accurate information about the mapped area's dimensions.

Instruction of laser scanning skills requires students to apply theoretical knowledge through hands-on exposure to laser scanner technology. This instruction must often be accomplished with the availability of few or no physical scanners. The limited availability of scanning instruments presents a challenge when class sizes are large, as the instrument-to-student ratio does not permit each student reasonable hands-on access. Also, when such courses are offered remotely, access to the equipment required to gain this exposure can impede the accomplishment of the stated course objective. At the Georgia Institute of Technology School of Building Construction Management, laser scanning is taught to students both at the undergraduate and graduate levels. A typical semester combined cohort size is approximately sixty-five students, yet the School posses only two instructional scanners.

The development of a digital demonstrator which could augment or replace a physical laser scanner was developed as a solution to the limited or non-availability of physical scanners. To accomplish this task, the researchers examined the current method of scanner instruction at the undergraduate and master's degree levels. A simulated scanner was then developed and tested by an initial introduction to a test group of high school students, followed by a graduate and an undergraduate class at the Georgia Institute of Technology. Student performance was measured using a mixed methods approach. The results of these tests are detailed in this article, along with conclusions concerning the effectiveness of a digital demonstrator for the instruction of laser scanning.

Background

Learning through a digital demonstrator is, in many ways, like simulation gaming. In gaming, the goal is to simulate a decision-making process and demonstrate the consequences of incorrect decisions. Kriz (2003) defines games as "the simulation of effects of decisions made by actors assuming roles that are interrelated with a system of rules and with explicit references to resources that realistically symbolize the existing infrastructure and available resources." There are two types of simulation games, open and closed. Open games lack a clearly defined ending and permit players to establish goals based on personal preference. The digital demonstrator is more similar to closed games as rigid rule simulation is incorporated. Players receive clear instructions which are based on well-defined rules. The problem statement is presented to the player within a well-defined framework. Participants must solve the problem precisely while adhering to the rules. The simulation model, rules, and flow are not stated explicitly in open, free-form games. Hence, a reflection phase is needed when teaching specific skills through gaming simulation. During reflection, participants can apply the knowledge acquired during the gaming simulation to the real world.

Digital demonstrators are also similar to flight simulators. Tiffen and McCormik (1986) discuss how learning with flight simulators require that students have the aptitude, ability, motivation, and opportunity to practice what they have been taught. They explain that the ability to put what has been learned into practice allows students to determine if they have achieved the level of knowledge necessary to make correct decisions. The authors describe that flight simulators must be designed to include specific learning goals required to perform a task. Flight simulators are also used as a testbed before actual flight validation. Ratvasky and Barnhart (2007) discuss how a concept demonstrator was used to understand deicing effects in an airplane to validate flight data results. By training with a digital demonstrator, pilots could understand how an aircraft handled in different icing conditions before they were at the helm of the aircraft. They could then provide verbal comments comparing their experiences in the simulator to those in-flight, and the data would be used to validate the pilot's flying decisions.

Training exercises have been demonstrated to be critical to gaining competence as part of knowledge transfer for complex skills. Advanced computing has recently enabled the integration of more serious games and simulations in skill training. The use of these tools has increased dramatically for training that is complex, time-critical and involves high risk. Simulators can now provide the learner with visualizations of the environment and the dynamics related to the user's actions (Aronsson, Artman, et all, 2021).

The availability of an open platform digital tool specific to laser scanning can be highly beneficial for construction faculty charged with introducing laser scanning in their courses. While digital demonstrators and simulators as teaching tools are not new, educators must expend valuable teaching/research time constructing such tools appropriate for the learning goals of their specific course (Wolffe, 2002). The digital demonstrator considered in this research is designed to address this issue for the instruction of laser scanning within construction courses at the university level.

Methodology

The work plan for this research is illustrated in Figure 1. It encompasses nine primary activities, including a literature review, identification of stakeholders, developing a digital prototype, conducting a cognitive walkthrough, a pilot test, prototype refinement, introduction to a graduate-level class, introduction to an undergraduate-level class, and the evaluation of test results.

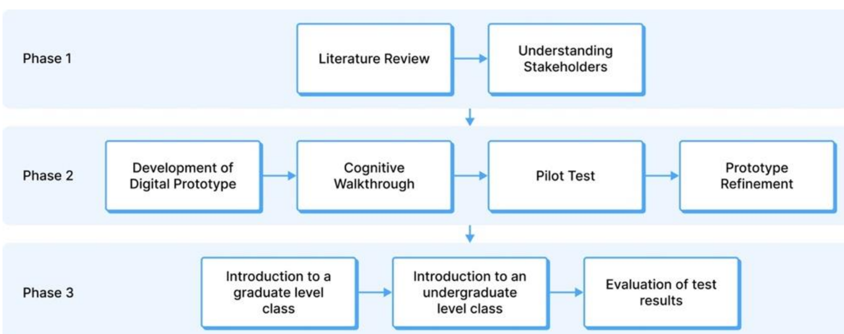


Figure. 1 Methodology

Understanding the Stakeholders

The initial task for this study was to understand the needs of the stakeholders who interact with laser scanners in the classroom. To accomplish this task, researchers observed instructors' and students' interaction using a physical scanner in a traditional classroom setting. Observation included a graduate course in Construction Tech, offered most semesters in the School of Building Construction Management at the Georgia Institute of Technology. Such traditional scanner instruction is performed using limited instruments compared to class size. It was determined that there are two stakeholders, instructors, and students. For instructors, it was observed to be desirable to develop a demonstrator with which the instructor can teach students the setup and operation of a laser scanner. Instructors should be able to use the tool to test students' knowledge of a scanner's operation for both formative and summative evaluations. Instructors should also have tools to measure proficiency in scanner operation. Students be able to access the laser scanner demonstrator both synchronously and asynchronously, as not all learning occurs during scheduled class time.

Development of a Digital Prototype

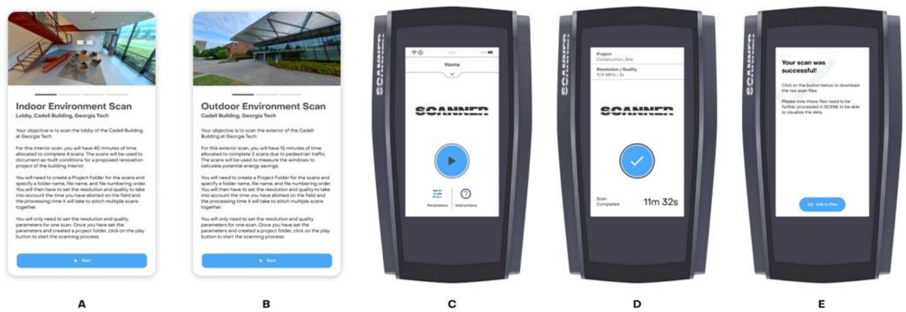
The results of the first phase, user analysis, informed the design decisions made in the design phase. Understanding the needs of both instructors and students, the researchers determined that designing multiple distinct operational modes would permit greater flexibility for all users. For this reason, an access mode and an assessment mode were developed. To reflect a variety of commercially available laser scanners, the design decision was made to develop a generic scanner inspired by available models but responsive to the needs of new users. The design phase was carried out in Figma, a tool that allows the development of wireframes. Wireframes were then carried over to Protopie, a high-fidelity prototyping tool commonly used in user interface design. High-fidelity interactions were designed using this Protopie software. The digital demonstrator is viewed on a browser window hosted on the Protopie cloud.

Figures 2A-F. Access mode screens

The first use mode of the demonstrator is the access mode. The access mode is an unrestricted mode aimed at instructional and practice usage. This mode has full access to the digital demonstrator and has no constraints on the device settings. All of the laser scanner settings can be modified by the users. Instructors can employ the access mode as a teaching tool during class instruction. Students can follow along during a lecture interacting with the laser scanner as they see beneficial. The access mode is depicted in Figure 2. Using the access mode, students can follow up after a lecture, further familiarizing themselves with the laser scanner at their own pace. The use of the access mode begins with the home screen.

The home screen (Figure 2A) is the main landing screen for the prototype and houses all the critical interactions of the laser scanner simulator. While on the home screen, users can access the scan button, represented by a blue play circle. Clicking on this button initiates the scan. The parameters button on the left lets the user choose from different settings required for a given scan scenario. These settings include resolution and quality, a user profile, the scan area, and the color mode. The view scan button lets the user preview the scans the scanner has taken. The user can select and view the information about the settings of the scans taken. The manage button allows the user to explore the settings of the scanner's user interface. Users can also add projects under which their scans will be housed, see operators' details for the device and explore the different preset scanning profiles. The help button in the top right corner of the home screen redirects users to this documentation if the users have any questions about the operation of the laser scanner simulator.

The next screen (Figure 2B) allows the setting of all scan parameters. This screen includes profile, resolution, quality, scan area, sensors that can be toggled on or off, and the option to scan in color. The screen illustrated in Figure 2C includes all resolution and quality selections. Students frequently find it challenging to visualize the relationship between resolution and quality. To help students with this visualization, a visualization feature has been added to the demonstrator. Students then progress to the next screen, which allows users to set administrative functions for the scanner (Figure 2D). This includes customization with the project (Figure 2E) and operator names. The profile button lets the user view several presets for scanning built into the laser scanner. The general settings allow the user to explore the settings of the scanner's user interface, including the date and time, screensaver, and language options. The final screen presents the scan progress (Figure 2F), indicating the status of the scan in progress to the user.



Figures 3A-E. Assessment mode screens

Supplementing the Access mode is the Assessment mode. The assessment mode is a restricted functionality mode aimed at enabling instructors to assess student proficiency in the operation of the laser scanner device. This mode can be used for evaluation at both the formative and summative stages of assessments. While in this mode, the user has a randomly assigned scenario that they must navigate (Figure 3A, Figure 3B). Access to settings not pertaining to these scenarios is restricted in this mode (Figure 3C). The assessment mode permits instructors to gauge students' proficiency using the laser scanner in one of the two randomly assigned senarios. Students can use this mode to measure their proficiency and ability to operate a laser scanner. When the student demonstrates operational proficiency in the digital demonstrator, they are rewarded with a data set identical to what a physical laser scanner device would provide at the successful completion of a laser scan activity. Students can then use this data set to advance to the data processing and analysis stages outside this demonstrator's scope (Figure 3D, Figure 3E).

Cognitive Walkthrough, Pilot Test, and Refinement

To identify design shortcomings, the researchers first conducted a cognitive walkthrough. Described by Lewis, Polson, Wharton, and Rieman in 1990, a cognitive walkthrough is a usability inspection method designed to bring together an interface evaluation and a cognitive model (Mahatody, 2010). Researchers presented the digital demonstrator interface to a graduate student with limited exposure to scanner use. The student was asked to perform a laser scanning task using the demonstrator tool. The student verbalized his actions and described why each action was selected. The research focus was on the cognitive activities of the student, including their goals and knowledge when performing each task. Errors were observed and recorded with particular attention to the cause of each error and the student's description of what they were looking for at the moment. Based on this analysis, several refinements were made to the digital demonstrator.

Following the cognitive walkthrough, the digital demonstrator was used to instruct a cohort of high school students on the use of a laser scanner. These students were selected as they allowed the researchers to access test subjects who were available at that time at the Georgia Institute of Technology building construction summer camp without exhausting the limited number of university-level construction students who could later participate in a more directed analysis of the tool. Clicks on the web-hosted prototype were monitored using Useberry, an online codeless prototype analytics platform based in Athens, Greece. Time on task and errors were recorded. Figure 4 illustrates the results of this pilot study. In general, the high school students found the prototype easy to moderately easy to use. Lack of motivation from students performing the learning task in the absence of course objectives or student grading was a limitation. Still, refinements were indicated, and the digital demonstrator was modified to reduce confusion and permit additional actions.

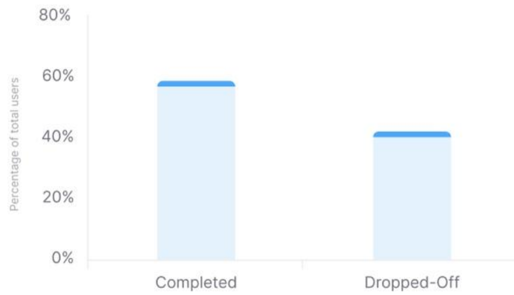


Figure 4. Pilot test completion rate

Implementation with Graduate and Undergraduate Students

Having conducted initial testing and refinement of the digital demonstrator, the resulting prototype was employed to instruct students in the use of laser scanning within courses at the Georgia Institute of Technology. The demonstrator was integrated into an undergraduate and graduate-level course during the fall 2022 semester. In both cases, the courses were on technology applications in building construction. During prior semesters, instruction in laser scanning relied on the use of FARO Focus laser scanners. The School of Building Construction Management owns two of these scanners. Students were first instructed using a PowerPoint presentation. After this, students gathered around a scanner provided in the classroom. Here they gained practical exposure to the setup of the physical scanner. Due to the availability of only two scanners, there are typically eight to fourteen students per scanner. Under these conditions, only a few students gain hands-on experience during instruction. With the digital demonstrator available, the instructor projected the digital demonstrator on a large screen in front of the class. Students used the online prototype of the scanner to accomplish tasks as discussed. Students then used the assessment mode to test their proficiency with the setup of a laser scanner. Each student's use of the access mode was tracked using the Useberry platform. Due to a technical issue with the interaction tracking platform, the researchers monitored only the graduate students while using the assessment mode. Some undergraduate students were not provided with the assessment mode. All the graduate students interacted with both the access and assessment modes.

Once the students completed using the digital demonstrator, they progressed to setting up a physical FARO laser scanner. They worked in teams of four to six students for this task. The teams then employed the FARO scanner to collect scanning data of an assigned area of the Cadell Building on the Georgia Institute of Technology campus. Once the data was collected, the graduate students were asked to provide verbal team feedback on using the digital demonstrator. Undergraduate students' feedback on the digital demonstrator was solicited using a written survey rather than verbal. Since not all the undergraduate students had been given hands-on access to the demonstrator, those who did not became the control group and formed a separate team for the purpose of data collection. The time required to set up the FARO scanner was monitored for each team, including the control group. After data collection, students worked individually to evaluate the scanning data, producing a model of their assigned portion of this building. Students were graded separately on data collection and processing, as well as project planning.

Results

Using the digital demonstrator with undergraduate students was shown to provide effective skill training. The students were able to interact with the digital scanner successfully. Those students who used the full digital demonstrator exhibited a far better understanding of the setup of the physical scanner based on observation. Figure 5 illustrates the time required to set up the Faro laser scanner. Teams one and two used the full digital demonstrator, while members of team three had not. Team three was less clear on how to set up a scanner and appeared to fumble along, making several corrections as they progressed. Teams one and two set up the physical scanner quickly and without error. The undergraduate students reported finding the digital demonstrator extremely easy to use and prepared them to interact with a physical scanner (Figure 6). Students reported that the demonstrator was a beneficial tool for learning laser scanner skills.

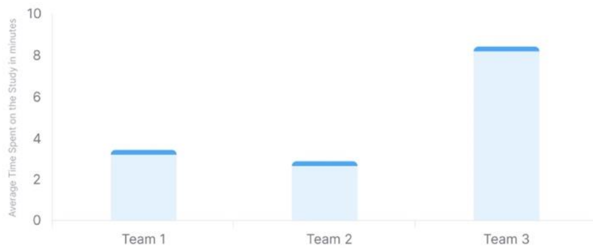


Figure 5. FARO scanner setup time

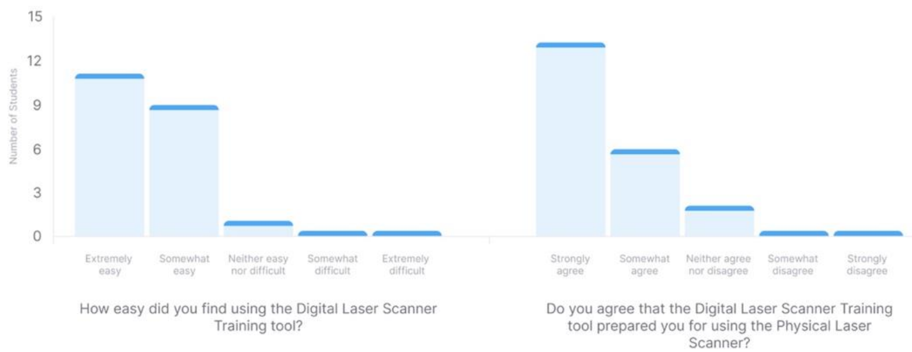


Figure 6. Student opinion on the digital demonstrator

Similarly, the graduate students found the scanner easy to interact with. Figure 7 illustrates the normal distribution of students' time on task when using the digital demonstrator. The graduate student's verbal evaluation of the digital demonstrator as a tool for learning how to set up a physical scanner is illustrated in Figure 8.

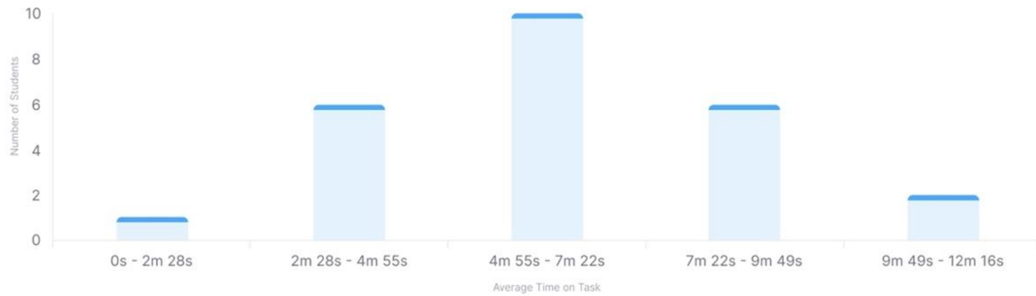


Figure 7. Time on task, assessment mode

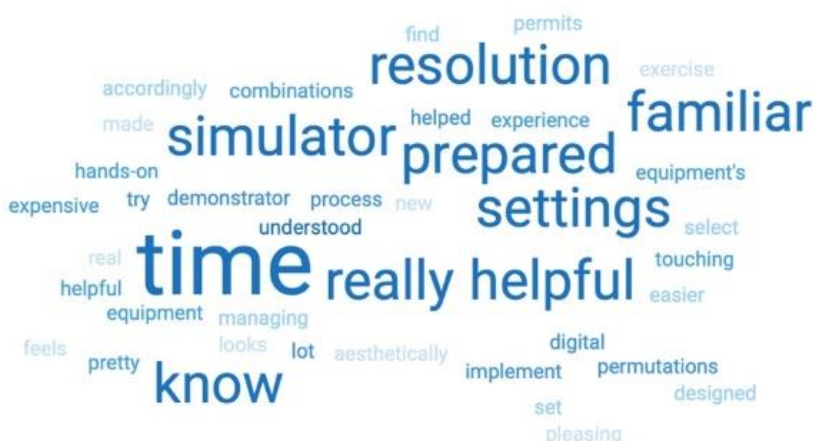


Figure 8. Word cloud of the student opinions

Conclusions

Integrating a digital demonstrator as an instructional tool for teaching students the correct setup and use of laser scanners proved to be helpful when applied in building construction management courses at the Georgia Institute of Technology. Testing documented that students found the demonstrator easy to understand and beneficial when first exposed to a FARO laser scanner. Students could quickly transfer the experience gained with the digital prototype to the setup of a physical scanner. Those students who completed full training on the digital demonstrator were able to set up the physical scanner more quickly than those with limited access to the prototype.

This experiment measured the success of a digital demonstrator in augmenting student exposure to a physical version of the same equipment. The same digital demonstrator could be applied as a replacement for a physical tool when access to costly equipment precludes such use in the classroom setting. The digital demonstrator was designed to provide students with a data set equivalent to what they would receive from a physical scanner. This makes it possible to prepare students for laser scanning using only the demonstrator. It is therefore recommended that the digital demonstrator be tested with students who do not have access to a physical scanner. This future research might include remotely offered instruction.

This research was limited to a single-use demonstrator. It is anticipated that similar success would be possible with digital demonstrators of other technology equipment in many areas of STEM education. Extension of the lessons learned from this study should be tested using other technologies standard in construction education. The demonstrator was designed to be used on a laptop computer screen. Several students did not bring laptops to class and relied on their smartphones when interacting with the digital demonstrator. This introduced unintended impediments to interacting with the online prototype. Future work would involve building a mobile version of the digital demonstrator to enable increased access. This study was also limited to a small student sample size. Expanding the sample size and supplying students with laptops should be considered to examine this topic further. Physical scanners other than the FARO model should also be included in future studies to validate compatibility with a wide range of scanners.

References

Aronsson, S., Artman, H., Brynielsson, J. *et al.* (2021). Design of simulator training: a comparative study of Swedish dynamic decision-making training facilities. *Cogn Tech Work* **23**, 117–130. https://doi.org/10.1007/s10111-019-00605-

Ebrahim, M. A. B. (2015). 3D laser scanners' techniques overview. *Int J Sci Res*, *4*(10), 323-331.

Kriz, W. C. (2003). Creating effective learning environments and learning organizations through gaming simulation design. *Simulation & Gaming*, *34*(4), 495-511.

Lewis, C., Polson, P. G., Wharton, C., & Rieman, J. (1990, March). Testing a walkthrough methodology for theory-based design of walk-up-and-use interfaces. In *Proceedings of the SIGCHI conference on Human factors in computing systems* (pp. 235-242).

Mahatody, T., Sagar, M., & Kolski, C. (2010). State of the art on the cognitive walkthrough method, its variants and evolutions. *Intl. Journal of Human–Computer Interaction*, *26*(8), 741-785.

Ratvasky, T., Barnhart, B., Lee, S., & Cooper, J. (2007, December). Flight testing an iced business jet for flight simulation model validation. In *45th AIAA Aerospace Sciences Meeting and Exhibit* (p. 89).

Tiffen, J., McCormik, E. (1986). "Industrial Psychology," *Unwin Books*

Wolffe, G. S., Yurcik, W., Osborne, H., & Holliday, M. A. (2002). "Teaching computer organization/architecture with limited resources using simulators." *Proceedings of the 33rd SIGCSE technical symposium on Computer science education* (pp. 176-180).

Assessment of Physical Demand in Bridge Rehabilitation Work by Physiological Status Monitoring

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Transportation construction projects involve long working hours where workers are subjected to intensive tasks such as hard manual work and compulsive working postures. Physically demanding work can be fatiguing as well as alter the mental state, which may, in turn, lead to decreased productivity, poor judgement, and ultimately more accidents and injuries. Therefore, monitoring and controlling physical demand is of paramount importance to sustain productivity without undermining workers' safety and health. The objective of this study is to apply a non-intrusive system to monitor and assess the physical demand of transportation construction workers using the percentage of Heart Rate Reserve (%HRR) as a measure. For this study, five bridge maintenance workers volunteered to record their physiological metrics while performing various construction and maintenance tasks. The case study results showed that bridge maintenance workers had an average daily %HRR over %30 which according to the literature can be considered as having a "high" cardiovascular load during an eight hour working day. The primary contribution of this research is the assessment of the physical demands of transportation construction workers with respect to acceptable physiological thresholds and boundaries. The application of the present approach can support construction workers in preventing excessive cardiovascular overload.

Key Words: Physical demands, Occupational health and safety, Wearable devices, Heart rate reserve, Transportation Construction workers

Introduction

The construction industry consistently maintains high rates of injuries and fatalities compared to other industries. Working on construction sites involves risk, can be physically demanding, and is significantly impacted by environmental conditions. Many construction activities involve heavy lifting, unusual work postures, vibrations, pushing and pulling, and forceful exertions (Hartmann and Fleischer 2005). Specifically, transportation construction projects involve long working hours where workers are subjected to intensive tasks such as hard manual work, heavy weightlifting, and compulsive working postures (Roja et al. 2006). These activities can result in fatigue and exhaustion due to their high physical demand. Some of these activities can cause immediate injuries, but most of these activities may adversely affect a worker over time. In addition to physical health, physically demanding work can also alter the mental state, which may lead to decreased productivity, poor judgement, inattentiveness, poor work quality, job dissatisfaction, and ultimately more accidents and injuries (Abdelhamid and Everett 2002). The transportation construction environment is generally more hazardous than most other work environments since the work is often conducted along active roadways and it involves the use of heavy equipment, dangerous tools, and hazardous materials, all of which increase the potential for accidents and injuries (Roja et al. 2006; Xing et al. 2020). In general, monitoring and controlling physical demand is of paramount importance to sustain productivity without undermining workers' safety and health (Meerding et al. 2005).

Recent advancements in Physiological Status Monitoring (PSM) have made it possible to measure physiological metrics of construction workers in real time. Several studies in the literature reported that PSM devices have the potential to be applied in construction sites to monitor physiological metrics with acceptable levels of error (Gatti, Schneider, and Migliaccio 2014; Hwang et al. 2016). Among the physiological metrics, heart rate is identified as a reliable indicator of physical demand and workload, and therefore, is widely used in physical demand measurement in the literature (Hsu et al. 2008; Zhu et al. 2017). For example, Hwang and Lee used a type of wristband PSM device to measure the heart rate of 19 construction workers to assess their physical demand over time. In this study, they used the percentage of heart rate reserve (%HRR) as a measure of physical demand. The study results indicated that the physical demand of construction workers significantly varies over time. Accordingly, they concluded that physical demand of construction workers need to be continuously monitored during workers' ongoing work to avoid safety and health risks (Hwang and Lee 2017). In a similar study, using a wristband PSM device, Lee et al collected the heart rate data and subjective perceived fatigue level of 12 workers over the period of two days. They applied heart rate reserve (%HRR) thresholds to identify the fatigue index for each of the time intervals. The correlation analysis indicated statistically meaningful correlation between the fatigue index and self-reported fatigue level (Lee, Lee, and Brogmus 2023).

Despite the contribution of these studies in assessing physical demand of construction activities, limited research exists on assessment of physical demand with respect to physiological acceptable thresholds and boundaries. Moreover, there is limited research assessing physical demand in transportation construction. The present study is conducted to address these existing gaps.

Research Objectives and Methodology

The objective of this study is to apply a non-intrusive system to monitor and assess the physical demand of transportation construction workers. Specifically, this study analyses the physical demand variations across different transportation construction activities performed during a bridge rehabilitation project with respect to acceptable physiological thresholds and boundaries. The Zephyr Bioharness was used to collect the physiological metrics of the workers such as heart rate, breathing rate, heart rate variability, and acceleration within the working hours. Although this device is originally designed to optimize the performance of professional athletes, several studies reported excellent reliability of using this device to measure heart rate and breathing rate (Lee, Lin, et al. 2017; Lee, Seto, et al. 2017; Pillsbury et al. 2020). The device is worn around the chest with the electrodes picking up the electrical signals from the heart. The collected physiological data can be transmitted to a smartphone, a fitness watch, or a computer for real time display or offline analysis (Zephyr 2016). Real time monitoring of the physiological metrics can enable workers or supervisors to prevent the exceedance of physiological thresholds to ensure safety and wellbeing of the workers. However, in the present study, offline analysis was performed since the objective of the paper is to evaluate the physical demand in bridge rehabilitation, and therefore the authors did not want to interfere with the common practice of the construction work.

Photographs with timestamps were also recorded to document the physical activities being performed to correspond to the heartrates recorded. Five bridge maintenance workers volunteered and gave consent to record their physiological metrics using a Bioharness while performing various construction and maintenance tasks. These volunteers were professional construction workers employed by the City and County of Denver. The experiment protocol for the study was reviewed and approved by the Institutional Review Board (IRB) at the University of Colorado Denver. Data collection was performed while the workers completed a bridge expansion joint replacement project from August 30, 2022 to September 2, 2022 in Denver, Colorado. Weather conditions were generally sunny and warm, with ambient temperatures ranging from 17 to 28 degrees Celsius over the course of the four days. The PSM harnesses were issued to the volunteers each morning, at the outset of the full day of construction activity. Upon completion of the work day, PMS harnesses were removed with log the data from individually numbered data puck. Volunteers received the same numbered puck during all data collection periods in order to ensure anonymity of data and allow effective collection of data across different activities. The schedule of construction and maintenance tasks are shown in Table 1. The demographic characteristics of participants are shown in Table 2.

Table 1

Schedule of performed construction activities in each day

Day	Performed Activities
1	Concrete demolishing and jackhammer operation
2	Concrete demolishing and jackhammer operation
3	Rebar work, expansion joint placement, and welding
4	Concrete placement and installing the expansion joint gland (joint seal)

The percentage of Heart Rate Reserve (%HRR) is used as a measure of physical demand. This method normalizes the original value of heart rate by the heart rate reserve of each individual (differences between maximum and minimum heart rate of each individual) to provide a relative measurement of physical demands, as shown in equation (1). This method measures the minimum heart rate at rest as a level with no physical intensity and demand. The Maximum heart rate is calculated based on the age of each individual (Tanaka, Monahan, and Seals 2001) as shown in equation (2) and Table 2. It should be noted that the collected heart rate data of different individuals are not comparable if not normalized as heart rate depends on the physical characteristics of each individual such as body size, age, and fitness levels. However, %HRR provides a relative metric that can measure the excessive cardiovascular load due to physical exertion by offsetting each individual's characteristics (Hwang and Lee 2017; Wu and Wang 2002).

$$\%HRR = \frac{HR - HR_{Rest}}{HR_{Max} - HR_{Rest}} \quad (1)$$

$$HR_{Max} = 208 - 0.7 \times Age \quad (2)$$

Where: $\%HRR$ is the percentage of Heart Rate Reserve; HR is the heart rate and is measured in units of beats/minute, HR_{Rest} is heart rate at rest; HR_{Max} is the maximum heart rate and can be calculated according to equation (2).

Table 2

Demographic characteristics of participants

Participant Number	Age	Weight (Kg)	Height (cm)	HR_{Rest} (bpm)	HR_{Max} (bpm)	BMI (kg/m^2)
1	28	77.1	175	51	188.4	25.1
2	36	113.4	160	64	182.8	44.3
3	33	115.6	188	63	184.9	32.7
4	33	92.5	180	53	184.9	28.4
5	39	90.7	180	62	180.7	28

Table 3

%HRR *Zones, thresholds, description, and respective suggestions**

%HRR Zones	%HRR Range	Description	Suggestions
Sedentary	0%-20%	Activities that have little movements and a low energy requirement (MET < 1.6)	An intensity that can be sustained over 60 minutes
Light	20%-40%	Activities that do not cause a noticeable change in breathing rate (1.6 < MET < 3)	An intensity that can be sustained over 60 minutes
Moderate	40%-60%	Activities that can be conducted whilst maintaining a conversation uninterrupted (3 < MET < 6)	An intensity that may last 30 to 60 minutes
Vigorous	60%-85%	Activities in which a conversation generally cannot be maintained uninterrupted (6 < MET < 9)	An intensity that may last up to 30 minutes
High	85%-100%	Activities that have a very high energy requirement (> 9 MET)	An intensity that generally cannot be maintained for longer than 10 minutes

*Adapted from (Norton et al. 2010)

For this study, the authors adopted the Norton et al. categories of physical activity intensity (Norton, Norton, and Sadgrove 2010) to evaluate the worker’s exposure to cardiovascular overload and overexertion. Norton et al. categorized the physical activity intensity based on objective measures such as %HRR, metabolic equivalent (MET), and subjective measures such as Borg rating of perceived exertion scale. This method classifies the intensity of physical activity into five categories including sedentary, light, moderate, vigorous, and high. Moreover, based on the literature, they specify safety suggestions for each of these categories. HRR thresholds, description, and respective suggestions are shown in Table 3. The aforementioned heart rate zones are used to investigate the variations of physical demands during a working day. It should be noted that workers' safety and health risks depend on both the physical demand and the duration of such intensity (Hwang and Lee 2017). To evaluate the overall physical demand of daily construction activities, average %HRR over the daily working hours is calculated. According to the literature, an average daily %HRR over %30 is considered as having a “high” cardiovascular load during an eight hour working day (Coenen et al. 2018; Gupta et al. 2014; Wu and Wang 2002).

Results and Discussion

Visualizations of the results show that the workers have similar trends and patterns of %HRR over the working hours, as shown in Figure 1. For example, the results show approximately 50% reduction in %HRR of each individual during the break times from 12:00 until 13:00. A comparison of timestamp photographs to the visual analysis of the collected data confirmed that %HRR is a good indication of the intensity of the physical activity. While general %HRR trends track across participants over time, %HRR for individual workers can vary at any point in time depending on the activity being performed; In other words, the workers %HRR can differently respond to same or similar work tasks compared to others. Discrete spikes in %HRR for individuals are observable when individuals are performing intensive tasks such as running the jackhammer or lifting heavy construction materials. Based on the heart %HRR zones defined in the methodology, workers’ exposure to cardiovascular overload were analyzed. The results of the first two days show that concrete demolishing and jackhammer operation require a high physical demand over all the duration of working hours. The third day required lower physical demand compared to the first two days. Based on the results, the most demanding task performed on the third day was the placement and adjustment of the expansion joint from 13:00 until 15:15, as shown in Figure 1. In the fourth day concrete placement was performed which required the lowest physical demand compared to the other days. In the fourth day, the most demanding task was installing the expansion joint gland (joint seal) from 14:45 until 15:15 after the concrete hardened.

Figure 2 shows cumulative time spent in a given %HRR zone. Only one participant (participant four) spent a recordable amount of time in the high %HRR zone. This occurred on the last day while trying to install the expansion joint gland (joint seal). It is also worth noting that the cumulative time of work intensity varied by worker. In other words, participants varied in which days they worked hardest. Despite the variations of physical demand among different individuals, day by day comparison of the results shows that the first two days had the highest portions of %HRR in the moderate and vigorous zones indicating higher demand of the performed activities. On average, all of the construction workers stayed in 0% to 60% of HRR zone over 80% of working hours, as shown in figure 2.

Figure 1. %HRR participants in each day

To have a better understanding of overall demand, average %HRR over the daily working hours was calculated for each of the participants in each day, as shown in Figure 3. It is possible to observe that the participant rank of average daily %HRR changes order most days. Nevertheless, average daily %HRR for all participants remains in the 30%-50% range, with the exception of participant one on the fourth day. According to the literature, this range of %HRR can be considered as having a "high" cardiovascular load during an eight hour working day (Coenen et al. 2018; Gupta et al. 2014; Wu and Wang 2002).

The %HRR results show that participants 1 to 4 had multiple occurrences of %HRR over 40% that were sustained over 30 minutes on days 1 to 3. This indicates excessive cardiovascular overload according to Norton et al. categories of physical activity intensity, as discussed in the methodology section. Therefore, interventions need to be made to reduce these workers' physical demands. This highlights the importance of continuous measurement of heart rate during workers' ongoing work and balancing workloads in order to prevent cardiovascular overload. To this end, a flexible work-rest schedule with frequent short breaks can be considered to avoid consistent high physical demand. Moreover, physiological demanding tasks need to be distributed as evenly as possible throughout the working days to prevent over even distribution of workload throughout different working days to prevent excessive physical demands at a certain day.

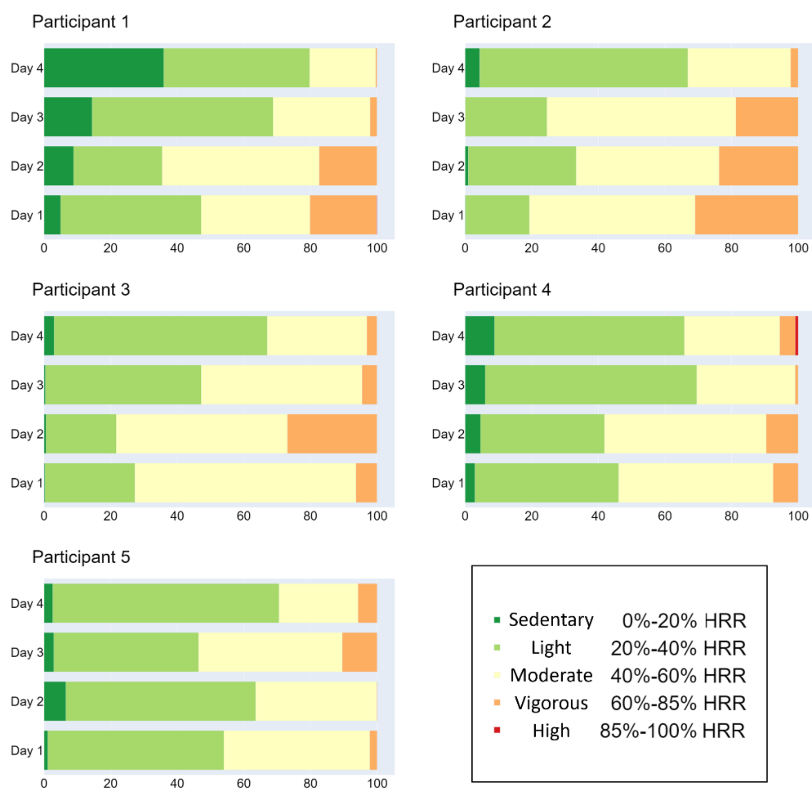

Figure 2. %HRR Zones for each of participants in each day

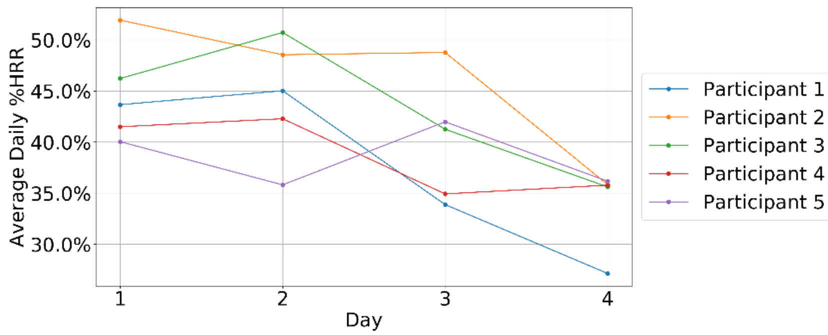

Figure 3. Average daily %HRR of participants in each day

Summary & Conclusions

The present study applied a non-intrusive system to monitor and assess the physical demand of transportation construction workers using the percentage of Heart Rate Reserve (%HRR) as a measure. To this end, five bridge maintenance workers volunteered and gave consent to record their physiological metrics while performing various construction and maintenance tasks on a bridge rehabilitation project. The results of the case study showed that workers' physical demands can be highly variable during working hours depending on the performed construction activity. Based on the results, bridge maintenance work can be classified as high demanding occupation with average daily %HRR over 30 percent. Moreover, the analysis of demand variations across different transportation construction activity showed that concrete demolishing and jackhammer operation caused the highest (spikes in) %HRR levels and also resulted in the highest average daily among other activities. According to the results, the majority of the participants had multiple occurrences of %HRR over 40% that were sustained over 30 minutes on days one to three which can be regarded as excessive cardiovascular overload. This highlights the importance of continuous measurement of heart rate during workers' ongoing work and balancing workloads in order to prevent overexertion. By recording and monitoring the physical demand of construction activities and comparing worker data to established benchmarks of physiological thresholds, companies will be better able to 1) assess individual health performance and risks, 2) compare the strenuousness of various construction activities, and 3) use such data to establish best practices for task assignment and durations under a variety of conditions to maximize the health and safety of their workers. This study can be extended to evaluate the effect of different work-rest schedules on reduction of cardiovascular overload.

References

Abdelhamid, Tariq S., and John G. Everett. 2002. “Physiological Demands during Construction Work.” *Journal of Construction Engineering and Management* 128(5):427–37.

Coenen, Pieter, Mette Korshøj, David M. Hallman, Maaike A. Huysmans, Allard J. van der Beek, Leon M. Straker, and Andreas Holtermann. 2018. “Differences in Heart Rate Reserve of Similar Physical Activities during Work and in Leisure Time – A Study among Danish Blue-Collar Workers.” *Physiology and Behavior* 186.

Gatti, Umberto C., Suzanne Schneider, and Giovanni C. Migliaccio. 2014. “Physiological Condition Monitoring of Construction Workers.” *Automation in Construction* 44:227–33.

Gupta, Nidhi, Bjørn Søvsø Jensen, Karen Søgaard, Isabella Gomes Carneiro, Caroline Stordal

Christiansen, Christiana Hanisch, and Andreas Holtermann. 2014. “Face Validity of the Single Work Ability Item: Comparison with Objectively Measured Heart Rate Reserve over Several Days.” *International Journal of Environmental Research and Public Health* 11(5).

Hartmann, Bernd, and Andreas G. Fleischer. 2005. “Physical Load Exposure at Construction Sites.” *Scandinavian Journal of Work, Environment & Health* 88–95.

Hsu, D. J., Y. M. Sun, K. H. Chuang, Y. J. Juang, and F. L. Chang. 2008. “Effect of Elevation Change on Work Fatigue and Physiological Symptoms for High-Rise Building Construction Workers.” *Safety Science* 46(5).

Hwang, Sungjoo, and Sang Hyun Lee. 2017. “Wristband-Type Wearable Health Devices to Measure Construction Workers’ Physical Demands.” *Automation in Construction* 83(August 2016):330–40.

Hwang, Sungjoo, Joon Oh Seo, Houtan Jebelli, and Sang Hyun Lee. 2016. “Feasibility Analysis of Heart Rate Monitoring of Construction Workers Using a Photoplethysmography (PPG) Sensor Embedded in a Wristband-Type Activity Tracker.” *Automation in Construction* 71(Part 2):372–81.

Lee, G., S. Lee, and G. Brogmus. 2023. “Feasibility of Wearable Heart Rate Sensing-Based Whole-Body Physical Fatigue Monitoring for Construction Workers.” Pp. 301–12 in, edited by S. Walbridge, M. Nik-Bakht, K. T. W. Ng, M. Shome, M. S. Alam, A. el Damatty, and G. Lovegrove. Singapore: Springer Nature Singapore.

Lee, Wonil, Ken Yu Lin, Edmund Seto, and Giovanni C. Migliaccio. 2017. “Wearable Sensors for Monitoring On-Duty and off-Duty Worker Physiological Status and Activities in Construction.” *Automation in Construction* 83(August 2016):341–53.

Lee, Wonil, Edmund Seto, Ken Yu Lin, and Giovanni C. Migliaccio. 2017. “An Evaluation of Wearable Sensors and Their Placements for Analyzing Construction Worker’s Trunk Posture in Laboratory Conditions.” *Applied Ergonomics* 65.

Meerding, W. J., W. IJzelenberg, M. A. Koopmanschap, J. L. Severens, and A. Burdorf. 2005. “Health Problems Lead to Considerable Productivity Loss at Work among Workers with High Physical Load Jobs.” *Journal of Clinical Epidemiology* 58(5).

Norton, Kevin, Lynda Norton, and Daryl Sadgrove. 2010. “Position Statement on Physical Activity and Exercise Intensity Terminology.” *Journal of Science and Medicine in Sport* 13(5).

Pillsbury, Wilbur, Caroline M. Clevenger, D. Ph, M. Asce, Moatassem Abdallah, D. Ph, A. M. Asce, Robert Young, and D. Ph. 2020. “Capabilities of an Assessment System for Construction Worker Physiology.” 34(2).

Roja, Zenija, Valdis Kalkis, Arved Vain, Henrijs Kalkis, and Maija Eglite. 2006. “Assessment of Skeletal Muscle Fatigue of Road Maintenance Workers Based on Heart Rate Monitoring and Myotonometry.” *Journal of Occupational Medicine and Toxicology (London, England)* 1:20.

Tanaka, Hirofumi, Kevin D. Monahan, and Douglas R. Seals. 2001. “Age-Predicted Maximal Heart Rate Revisited.” *Journal of the American College of Cardiology* 37(1).

Wu, Hsin Chieh, and Mao Jiun J. Wang. 2002. “Relationship between Maximum Acceptable Work Time and Physical Workload.” *Ergonomics* 45(4).

Xing, Xuejiao, Botao Zhong, Hanbin Luo, Timothy Rose, Jue Li, and Maxwell Fordjour Antwi-Afari. 2020. “Effects of Physical Fatigue on the Induction of Mental Fatigue of Construction Workers: A Pilot Study Based on a Neurophysiological Approach.” *Automation in Construction* 120.

Zephyr. 2016. “OmniSense Live Help.” *Zephyr Technologies*.

Zhu, Yibo, Rasik R. Jankay, Laura C. Pieratt, and Ranjana K. Mehta. 2017. “Wearable Sensors and Their Metrics for Measuring Comprehensive Occupational Fatigue: A Scoping Review.” in *Proceedings of the Human Factors and Ergonomics Society*. Vols. 2017-October.

Physiological Metrics Across Construction Activity

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Safety management and occupational health are essential for construction work. Several studies examine the extent to which physical activity impacts the health and safety of construction workers. To date, however, few studies directly assess the impact of construction activities. This research analyzes physiological and environmental data to explore the impact of construction activity on individual workers, under a range of ambient conditions. Vital signs and physical indicators including heart rate, breathing rate, core temperature, physiological load, mechanical load and posture were collected from a relatively homogeneous set of US Air Force Academy cadets while performing four different construction activities. Results suggest average physiological measures (i.e. mean Heart Rate, Breathing Rate etc.) statistically vary by individual even for individuals similar in age, health, and fitness. Despite individual distinctions, statistical trends and patterns are observable across construction activities. Specifically, the results demonstrate that concrete and asphalt placement are generally more physically demanding, followed by, heavy equipment operation and surveying activities respectively. In addition, the ambient variable, Heat Index, plays a significant role and merits future research. The primary contribution of the research is to demonstrate a method for monitoring and assessing discrete physiological metrics across individuals as well as construction activity.
Key Words: Construction Worker Health, Physiological Metrics, Safety, Physiological status monitoring technology

Introduction

Many construction activities require extensive physical labor over extended periods, sometimes with exposure to adverse weather conditions. Construction, in general, is a labor intensive process where workers are subjected to unusual work postures, heavy weight lifting, and a range of work postures (Hartmann and Fleischer 2005). Injuries from construction activity can be immediate or cumulative over time. Physical stress and strain can lead to decreased work productivity, inattentiveness, or inability to make wise decisions. Construction productivity is generally measured as the number of hours of work required to complete a specified work product (Jang et al., 2011). While productivity is not directly measured in this research, it is well-documented that the typical, demanding workload of construction can take a toll on both the mental and physical health of a worker. Furthermore, continuous depression and dissatisfaction from a worksite can result in unwanted accidents and more injuries (Abdelhamid and Everett 2002). Construction workers are exposed to ergonomic hazards, which include dynamic movement, various unusual postures, pulling and lifting loads (Hartmann and Fleischer 2005). They are at risk to develop musculoskeletal disorders (Engholm and Holmström 2005).

A number of studies focused on analyzing the impact of construction work on workers using physiological indicators such as heart rate, body temperature, and blood oxygen level (Abdelhamid and Everett 2002; Buller et al. 2010; Kirk and Sullman 2001). For example, Abdelhamid and Everett (2002) collected oxygen consumption and heart rate data to determine the performance of 100 construction workers doing moderate to heavy work. The data showed that the average oxygen uptake was 0.82 L/min (± 0.22 L/min) and the average heartbeat was 108 beats/min (± 17 beat) min). Measurements were compared to standard guidelines for acceptable levels of physical performance for specific industrial environments. Results indicated that 20-40% of the workers regularly exceeded recommended thresholds for manual work, thereby making the workers more prone to inattentiveness, decreased productivity, poor judgment, accidents, and injuries. Several research works studied the factors affecting heat stress (Rowlinson et al. 2014; Yi et al. 2016; Yi and Chan 2015). For example, Rowlinson et al. (2014) studied factors affecting climatic heat stress and identified three ways of reducing heat stress in construction sites: (1) control of climatic heat stress exposure through the use of an action-triggering threshold system, (2) control of continuous work time with mandatory work-rest routine, and (3) allow workers to follow self-pace regimes. Other studies considered additional indicators such as posture to evaluate the health hazards among construction workers (Roja et al. 2006; Tak et al. 2011). For example, Roja et al. (2006) conducted a study on workers from the heavy civil industry which included ten road construction and maintenance workers and ten pavers who belonged from the age group 20-60 years. The study measured the physical demands of road construction work and estimated muscle fatigue. Average metabolic energy consumption for road construction and repair work was recorded as 8.1± 1.5 kcal/min, and 7.2 ± 1.1 kcal/min for paving respectively. Their findings documented that road construction work requires extreme manual labor, compulsive working posture, and continuous arm and leg movements. In the same study, they monitored the workers' heart rate, posture and muscle tone for a week and suggested that work-related musculoskeletal problems could be likely for these workers. Several studies applied physical monitoring systems (PMS) for the purpose of physiological monitoring, environmental sensing, proximity detection and location tracking analysis on construction workers (Aryal, Ghahramani, and Becerik-Gerber 2017; Awolusi, Marks, and Hallowell 2018; Lee and Migliaccio 2016; Wang et al. 2017; Yu et al. 2017). For example, Gatti et al. (2014) investigated the validation of PMSs for construction based on two physiological parameters including heart rate and breathing rate. Results indicated that PMS data can be used to identify and correlate physical strain, task level, productivity, and safe-unsafe behavior of construction workers.

Although the aforementioned studies had significant contributions in examining the extent to which physical activity impacts the health and safety of construction workers, there are limited studies that focused on monitoring and collecting physiological data of workers across different construction activities under a range of ambient conditions. Moreover, former studies have primarily been limited to one or more physical indicators of the construction workers. The present research focuses on the analysis of multiple physical indicators across four construction activities.

Research Objectives and Methodology

The objective of this research is to develop and advance a system that analyzes physiological and environmental data to explore the impact of construction activity on individual workers, under a range of ambient conditions. For this research, the system was applied to a relatively homogenous set of workers, in this case, a set of ten US Air Force Academy (USAFA) cadets comprised of 8 males and 2 females, who each performed four distinct construction activities under similar, relatively controlled, conditions. International Review Board protocols for research involving humans were completed under the supervision of USAFA. During the study period, volunteers were following similar food and sleep regimens. All the volunteers were within the age range of 20-22. The following metrics were analyzed: heart rate, breathing rate, core temperature, mechanical load, physiological load, and posture. Metric descriptions are provided in Table 1, based on research and available manufacturer information (Zephyr 2013).

Table 1

Metrics

Metric	Description	Units	Notes
Heart Rate	It is measured as the number of heart beats per minute.	Heartbeats per minute	The measure of Heart rate is analyzed from the 250Hz Echocardiogram (ECG) data
Breathing Rate	It is measured as the number of breaths per minute.	Breathing per minute	The sensors inside the zephyr puck detect breathing by the expansion and contraction of our torso.
Posture	It is measured as the change of angle of any individual in comparison with gravity.	Degree from the vertical position.	When an individual is standing straight the measurement is zero. Forward and backward leaning accounts for positive and negative values.
Core Temperature	The core temperature is estimated based on the heart rate.	Degree Centigrade	The accuracy of this estimate and have also demonstrated that such a computational measurement can indicate physical stress before an individual reaches an unhealthy state (Buller and Hoyt 2008).

Volunteers' physiological characteristics were monitored during four construction activities. Table 2 defines these activities based on USAFA's FERL handbook descriptions ("Civil Engineering Practices - Field Engineering Cadet Handbook," 2017).

Table 2

Construction Activities

Activity	Description
Concrete Placement (C)	Prepare a site, set framework and reinforcement, place concrete, and take samples and perform slump test.
Heavy Equipment (HE)	Operate construction equipment including an excavator, scraper, bulldozer, loader, and paving machine.
Surveying (S)	Use total station to measure distance and horizontal/vertical angles. Layout a calculated location for concrete slab pour and use measuring techniques to plot land data.
Asphalt Paving (A)	Place a section of road using approximately 20 tons of asphalt.

The PMS device used for this study was the Zephyr BioHarness, an off-the-shelf product capable of remote physiological monitoring and location tracer without hindering the flexibility and freedom of the individual (Zephyr 2013, 2016). To retrieve the recorded data from PMS devices, and to analyze the physiological status for each volunteer, "Omnisense" software was used (Zephyr 2016). To this end, individual weight, height, age, and fitness levels of the volunteers were entered into the software. Based on the collected data, the software generated spreadsheets including, heart rate, breathing rate, posture, core temperature, and Heart Rate Confidence (HRC) for each of the volunteers. HRC is calculated based on electrocardiogram noise and worn detection. The threshold for accepting data was based on HRC of 80% or higher, based on the recommendation of Zephyr's representative. Lower HRC levels suggest the data is unreliable based on the faulty collection. This indicator is then used to remove the noisy data. After the data collection phase, software R was used to perform statistical analyses in 5 steps: (1) filter the noisy data based on HRC; (2) aggregate one-second interval data to one-minute interval data; (3) add morning and afternoon weather, temperature, humidity level, and heat index using local station data; (4) apply a Linear Mixed Effect Model (LMM) to analyze the effect and statistical significance of the independent variables including heat index and activity on the physiological metrics such as heart rate, breathing rate, posture, and core temperature per individual and construction activity; and (5) compare data and identify general and observable patterns.

Model Development

Multivariable linear regression is predominantly used to model the relationships among two or more explanatory variables and a response variable by fitting a linear equation to the observed data. For the collected data, there are repeated observations over time for an individual which cannot be assumed to be independent. An appropriate way to model such repeated measures data across time is the use of the linear mixed-effects model. The Linear Mixed Effect Model (LMM) comprises both fixed effects and random effects. The random-effects take care of the correlation between the repeated observations. For this study, the goal was to determine the effect of the independent variables such as gender, heat index, activity level and activity on the metrics. The LMM, therefore, can be written as shown in Equation 1.

$$Y_{ij} = \beta_0 + \beta_1 gender + \beta_2 H.I + \beta_3 A.L + \beta_4 A1 + \beta_5 A2 + \beta_6 A3 + \beta_7 A4 + b_i + \epsilon_{ij} \qquad (1)$$

Where: Y_{ij} is the value of the response for the jth replication for ith individual; A1, A2, A3, and A4 are activity 1 to 4, respectively, and can have the value of 1 if the volunteer does the corresponding activity, and otherwise 0; gender is 1 for male and 0 for female; H. I is Heat Index; A. L is Activity Level; b_i is individual specific random effect for the ith individual; and ϵ_{ij} is the error (residual).

Likelihood Ratio Test (LRT) was used to determine if an outcome was statistically different from other outcomes. If a significant difference between activity outcomes was found, a pairwise comparison (t-test) was then used. To adjust raw p-values when testing various hypotheses, a Bonferroni correction (Dunn 1961) was used.

Results and Discussion

This research analyzed unique data sets to explore statistical relationships and observable patterns for physiological metrics variables as measured in construction workers of similar in fitness, age, and experience, performing four distinct construction activities. Violin plots representing the distribution of heart rate, breathing rate, core temperature, and posture across the four activities are shown in Figure 1. Violin plots visualize the distribution of the data and present a vertically symmetric probability distribution of the response variable as estimated from the data. These results indicate that concrete placement is the most physically demanding activity for all volunteers.

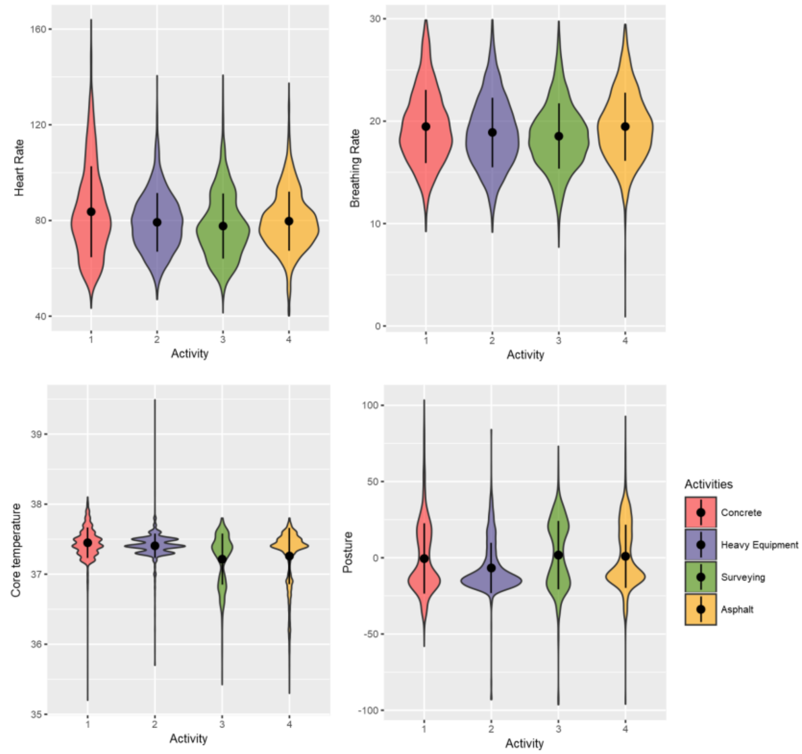

Figure 1. Violin plot showing the distribution of heart rate, breathing rate, core temperature, and posture across the four activities

To test for statistical differences t-test was performed for the heart rate, breathing rate, core temperature, and posture data across all 10 volunteers. The p-values indicate that: (1) heat index, activity level and activity are significantly associated with heart rate ($p \leq 0.05$), but gender is not significantly associated ($p > 0.05$). (2) heat index, activity level and activity are significantly associated with breathing rate ($p \leq 0.05$), but gender is not significantly associated ($p > 0.05$). (3) activity is significantly associated with core temperature ($p \leq 0.05$). (4) heat index, activity level and activity are significantly associated with posture ($p \leq 0.05$), but gender is not significantly associated ($p > 0.05$).

Pairwise comparisons between the different activities were performed to investigate which activities lead to significantly different heart rates, breathing rates, core temperature, and posture. The pairwise comparisons indicate that: (1) concrete-heavy equipment, concrete-surveying, heavy equipment-surveying, heavy equipment-asphalt result in statistically distinct heart rate profiles; (2) concrete-surveying, heavy equipment-surveying, surveying-asphalt result in statistically distinct breathing rate profiles from one another; (3) concrete- heavy equipment, concrete-surveying, concrete- asphalt, heavy equipment-surveying, and surveying-asphalt result in statistically distinct posture profiles; and (4) concrete-surveying, concrete-asphalt, heavy equipment-surveying, heavy equipment-asphalt, surveying-asphalt result in statistically distinct core temperature profiles from one another with the core temperature profiles during surveying and asphalt being the most distinct. Moreover, results suggest that heat index also affects the physiological metrics of individuals when performing construction activities.

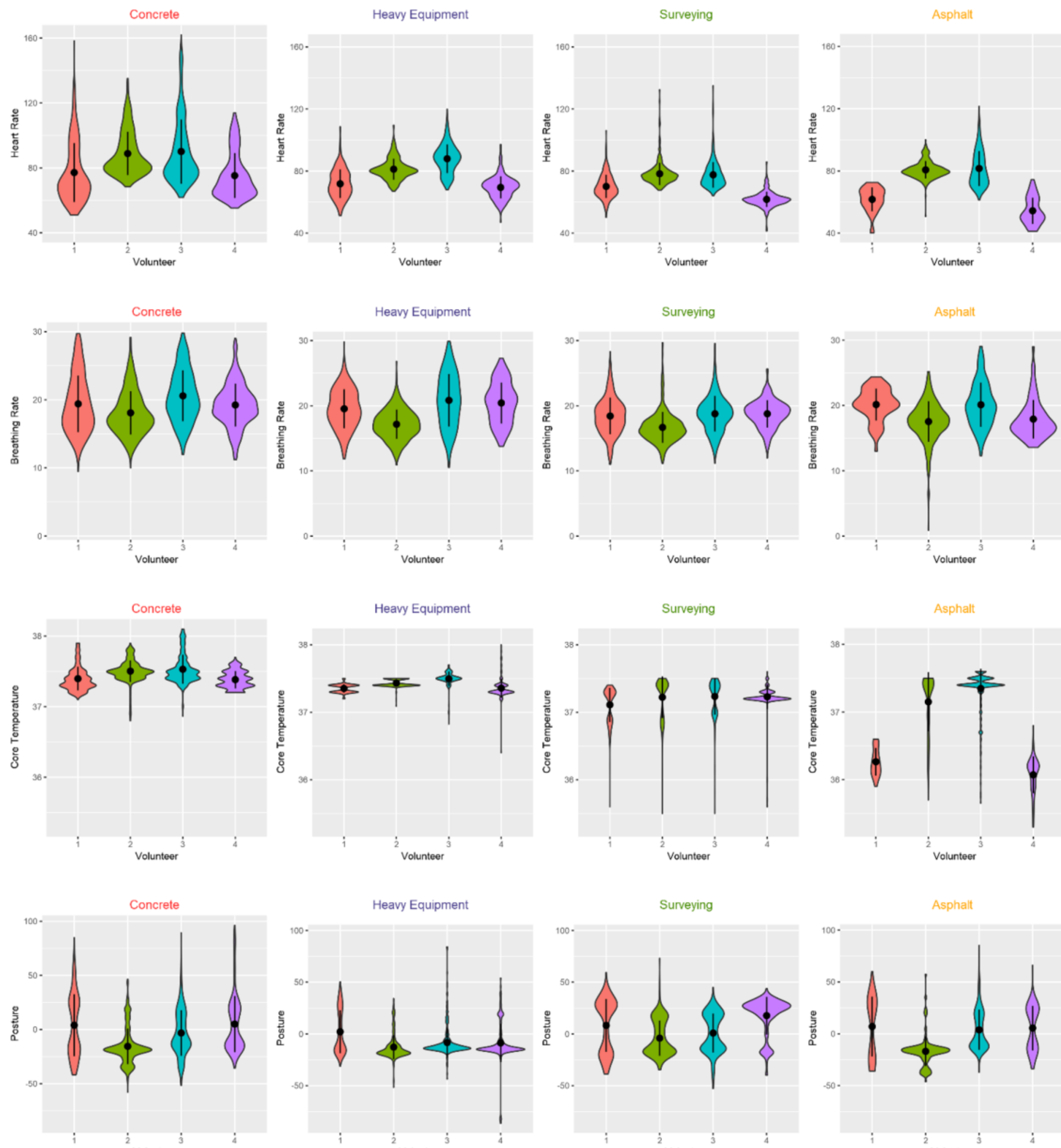

Figure 2. Violin plot showing the distribution of heart rate, breathing rate, core temperature, and posture for volunteers 1,2,3,4 across the four activities

In addition to the full analysis of the 10 volunteers, a focused analysis of the data from four volunteers who were in the same group was performed to minimize the role of external variables (such as weather, time of day, specific tasks performed etc.). Specifically, volunteers 1, 2, 3 and 4 were all working under the same climatic conditions and synchronously performing the same construction activities. Moreover, volunteers 1,2,3, and 4 were all male. Figure 2. shows the violin plots for each metric for the four volunteers performing concrete, heavy equipment, surveying, and asphalt activities to visually compare individual differences and patterns. A more in-depth look at the four volunteers performing construction activities concurrently confirms the results, suggesting that the research data collection and analysis method is capable of correctly identifying patterns for the impact of construction activities on construction workers. In particular, a general trend exists demonstrating that the mean heart rate for certain individuals (volunteers 2 and 3) is greater than others (volunteer 1 and 4) across all activities, but that patterns of the impacts of construction activity persist despite these individual differences. Similarly, Figure 2 shows that the mean posture metric for volunteers 1 and 4 is greater than volunteers 2 and 3 across all activities. In contrast, operating heavy equipment results in a posture that is the most reclined for nearly all volunteers.

Such results suggest that the studied metrics and methods are effective at assessing the impact of construction activities on individuals' physiological health. Furthermore, the study shows that it is possible to independently compare discrete physiological metrics across individuals performing activities under various weather conditions. In short, the research serves to highlight the significant opportunity to use the proposed research methods to study construction worker health and productivity in future studies.

While the longitudinal data from only four volunteers are based on a limited sample size, the similarity in conditions makes this data potential less confounded. Furthermore, the large number of data points collected for each volunteer still enables statistical comparison between and among metrics. In short, when heart rate is compared for the four volunteers (Figure 2), there is a clear pattern showing that heart rates for volunteers 1 and 4 are consistently lesser, on average, compared to volunteers 2 and 3. We can conclude that heart rate, in general, is higher for volunteers 2 and 3 irrespective of activity type. However, this general trend is shifted up or down based on the activity (although less so for Asphalt), suggesting that while individuals have different physiological norms, construction activities may impact distinct individuals in a similar manner, albeit, potentially, to differing extents. For example, the heart rates of all four volunteers are lower, on average, for surveying. Also, the heart rates reach a much higher value for concrete compared to other activities. Similar patterns are noticed for breathing rate and core temperature.

Finally, pairwise comparisons between the different activities were performed for the four volunteers to investigate which activities lead to significant differences. While perhaps not generalizable, results from pairwise comparisons p-values indicate: (1) all pairs of activities except asphalt and concrete yield significantly different heart rates; (2) all pairs of activities except surveying yield significantly different breathing rates. (3) all pairs of activities yield significantly different core temperatures. (4) asphalt-concrete and asphalt-surveying have similar posture and heavy equipment yields the most significant difference in posture.

Future Work

The present research provides a potentially transformative model for supporting the occupational health of construction workers and motivates future research in the area. In future work, additional methods, such as mutual information from information theory, will be applied to evaluate the impact and influence of independent variables on physiological metrics to provide a more thorough analysis. Moreover, there is a need for future research on the impact of working environments on workers due to the variety in types of construction projects. For example, in highway infrastructure projects, workers are exposed to the risk of injury from the movement of construction vehicles and equipment within the work zones, as well as from passing motor vehicle traffic. Therefore, the working condition in this type of project is expected to increase the stress levels in workers. Finally, the current research can be expanded to collect more data on different activities from different types of construction projects. Using pattern recognition methods such as machine learning algorithms, the collected data can be used to predict or assess when health or performance thresholds are about to be reached or exceeded. In particular, such research will assist managers in scheduling workers to maximize productivity and minimize workplace injuries under extreme weather or working conditions. Moreover, these data can be used to establish indicators and real-time warning systems to help minimize potential physical harm to construction workers.

Summary & Conclusions

This study presented the development of a new system that uses physiological and environmental data to explore the impact of construction activities on individual workers, under a range of ambient conditions. The system was applied to a relatively homogenous set of workers, in this case, a set of ten US Air Force Academy (USAFA) cadets comprised of 8 males and 2 females, who each performed four distinct construction activities under similar, relatively controlled, conditions. Vital signs and physical indicators including heart rate, breathing rate, core temperature, physiological load, mechanical load and posture were collected and analyzed. To this end, software R was used to perform statistical analyses in 5 steps: (1) filter the noisy data based on HRC; (2) aggregate one-second interval data to one-minute interval data; (3) add morning and afternoon weather, temperature, humidity level, and heat index using local station data; (4) apply a Linear Mixed Effect Model (LMM) to analyze the effect and statistical significance of the independent variables on the physiological metrics; and (5) compare data and identify general and observable patterns. Research analysis suggests that heat index and construction activities have a measurable effect on the physiological metrics of individuals with similar physical characteristics. Specifically, results indicate that among the four different construction activities studied, concrete and asphalt paving are more physically demanding activities as compared to operating heavy equipment and surveying activities. Notably, looking at four volunteers working under similar climatic conditions revealed similar statistical and observable patterns for physiological metrics across construction activities. The results of this study suggest that such a research method yields statistically significant patterns and is capable of documenting the effects of construction activity as well as ambient conditions on individual construction worker health and performance. Such research will be critical in establishing physiological thresholds for construction workers while performing a range of activities under various climatic conditions.

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References

Abdelhamid, T. S., and J. G. Everett. 2002. “Physiological Demands during Construction Work.” *Journal of Construction Engineering and Management* 128(5):427–37.

Anon. 2017. “Civil Engineering Practices - Field Engineering Cadet Handbook.”

Aryal, Ashrant, Ali Ghahramani, and Burcin Becerik-Gerber. 2017. “Monitoring Fatigue in Construction Workers Using Physiological Measurements.” *Automation in Construction* 82:154–65.

Awolusi, Ibukun, Eric Marks, and Matthew Hallowell. 2018. “Wearable Technology for Personalized

Construction Safety Monitoring and Trending: Review of Applicable Devices." *Automation in Construction* 85(July 2016):96–106.
Buller, M. J. .. B., W. J. .. Tharion, R. W. .. Hoyt, and O. .. Chadwicke Jenkins. 2010. "Estimation of Human Internal Temperature from Wearable Physiological Sensors." *Proceedings of the National Conference on Artificial Intelligence* 3:1763–68.
Buller, Mark J., and Reed W. Hoyt. 2008. "Estimation of Human Internal Temperature from Wearable Physiological Sensors." 1763–68.
Dunn, Olive Jean. 1961. "Multiple Comparisons among Means." *Journal of the American Statistical Association* 56(293):52–64.
Engholm, Göran, and Eva Holmström. 2005. "Dose-Response Associations between Musculoskeletal Disorders and Physical and Psychosocial Factors among Construction Workers." *Scandinavian Journal of Work, Environment and Health* 31(SUPPL. 2).
Gatti, Umberto C., Giovanni C. Migliaccio, Susan M. Bogus, and Suzanne Schneider. 2014. "An Exploratory Study of the Relationship between Construction Workforce Physical Strain and Task Level Productivity." *Construction Management and Economics* 32(6):548–64.
Hartmann, Bernd, and Andreas G. Fleischer. 2005. "Physical Load Exposure at Construction Sites." *Scandinavian Journal of Work, Environment & Health* 88–95.
Jang, H., Kim, K., Kim, J. and Kim, J. (2011), "Labour productivity model for reinforced concrete construction projects", Construction Innovation, 11(1): 92-113.
Kim, J. H., R. Roberge, J. B. Powell, A. B. Shafer, and W. Jon Williams. 2013. "Measurement Accuracy of Heart Rate and Respiratory Rate during Graded Exercise and Sustained Exercise in the Heat Using the Zephyr BioHarness™." *International Journal of Sports Medicine* 34(6):497.
Kirk, Patrick M., and Mark J. M. Sullman. 2001. "Heart Rate Strain in Cable Hauler Choker Setters in New Zealand Logging Operations." *Applied Ergonomics* 32(4):389–98.
Lee, Wonil, and Giovanni Ciro Migliaccio. 2016. "Physiological Cost of Concrete Construction Activities." *Construction Innovation* 16(3):281–306.
Roja, Zenija, Valdis Kalkis, Arved Vain, Henrijs Kalkis, and Maija Eglite. 2006. "Assessment of Skeletal Muscle Fatigue of Road Maintenance Workers Based on Heart Rate Monitoring and Myotonometry." *Journal of Occupational Medicine and Toxicology (London, England)* 1:20.
Rowlinson, Steve, Andrea Yunyanjia, Baizhan Li, and Carrie Chuanjingju. 2014. "Management of Climatic Heat Stress Risk in Construction: A Review of Practices, Methodologies, and Future Research." *Accident Analysis and Prevention* 66:187–98.
Tak, Sang Woo, Bryan Buchholz, Laura Punnett, Susan Moir, Victor Paquet, Scott Fulmer, Helen Marucci-Wellman, and David Wegman. 2011. "Physical Ergonomic Hazards in Highway Tunnel Construction: Overview from the Construction Occupational Health Program." *Applied Ergonomics* 42(5):665–71.
Wang, Di, Jiayu Chen, Dong Zhao, Fei Dai, Changjian Zheng, and Xiaobing Wu. 2017. "Monitoring Workers' Attention and Vigilance in Construction Activities through a Wireless and Wearable Electroencephalography System." *Automation in Construction* 82:122–37.
Yi, Wen, and Albert P. C. Chan. 2015. "Optimal Work Pattern for Construction Workers in Hot Weather: A Case Study in Hong Kong." *Journal of Computing in Civil Engineering* 29(5):05014009.
Yi, Wen, Albert P. C. Chan, Xiangyu Wang, and Jun Wang. 2016. "Development of an Early-Warning System for Site Work in Hot and Humid Environments: A Case Study." *Automation in Construction* 62:101–13.
Yu, Yantao, Hongling Guo, Qinghua Ding, Heng Li, and Martin Skitmore. 2017. "An Experimental Study of Real-Time Identification of Construction Workers' Unsafe Behaviors." *Automation in Construction* 82(July 2016):193–206.
Zephyr. 2013. "BioHarness BT User Guide."
Zephyr. 2016. "OmniSense Live Help." *Zephyr Technologies*.

Solutions for Maintaining Productivity in a Shrinking Workforce

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Construction companies work in a highly competitive market and often the smallest difference in how they approach project cost and productivity can determine their success. Also some of these companies struggles to take advantage of efficiencies in productivity when the gains cannot be easily observed. Within academia, there is an ongoing trend toward research that focuses on productivity and innovation that tackles some of the well know issues plaguing the industry. More recently, the labor supply worldwide is struggling to keep pace with the demand for construction services. In this research, four potential solutions addressing the labor shortage were identified in the current literature on robotics, off-site construction, wage re-evaluation, and vocational education. The study gathered electronic survey data from industry professionals concerning these potential solutions and discerned that off-site construction, wage re-evaluation, and vocational education seemed to be favorable options, while robotics were perceived as not ready yet. The remainder of the paper analyzes these results and provides some additional context to the responses from the various open-ended questions that were also collected during the study.

Key Words: Sustainable Labor Practices, Labor Productivity, Labor Efficiency, Labor Shortage, Construction Workforce

Introduction and Background

The construction industry is one of the fastest-growing industries in the United States. From 2020 to 2021, industry spending rose by 1.3% to $1.45 trillion (Beaudoin, 2021). The trouble with this growth is that construction companies are struggling to maintain the workforce necessary to meet the demand of the growing industry. The Association of General Contractors of America surveyed 2018 general contracting firms and found that eighty percent of them had trouble finding qualified, skilled labor (Callanan et al., 2020). For instance, in 2021, just to keep up with the growing economy, more than 430,000 workers were needed in construction in the United States (Beaudion, 2021). This number was not met and will continue to increase in 2022. The growing labor shortage continues to create and worsen the schedule of work and budget overruns (Kim et al., 2020). These continued schedules and budget overruns lead to rising project costs and worsen the inherent obstacles associated with construction projects, including road closures, environmental impacts, and loss of revenue for the owner. The remainder of this section will highlight some potential workforce solutions found in the existing literature, along with advantages and disadvantages.

The first proposed solution is the use of robotics in construction. The use of robotics to replace human labor has the potential to reduce the number of people needed in construction as well as free up available labor to do other tasks that automation cannot. Also, the use of robotics adds a safety benefit because humans are not involved in some of the more dangerous tasks in construction. The use of robotics, however, is met with persisting opposition to new technology being introduced to the conventional construction practice (Brissi et al., 2022). Also, the technology is not sufficiently developed for full-scale use. When it is fully developed, there will be a production period before robotics are seen in numbers on construction sites. However, the early adoption of robotics could lead to an increase in research and development that would expedite the process significantly.

The second proposed solution is the increased use of off-site construction and prefabrication. Off-site construction is currently being practiced and is expected to grow to $157 billion by the end of 2023 (Saad et al., 2021). Some contend that with off-site construction, a house could be built with less labor, 25% less budget, and in only 24 hours (Saad et al., 2021). The technology for this exists today, however, the industry and owners are apprehensive because the workflow and processes are still being refined. Also, the long-term resilience of this type of construction remains unknown, and some argue that off-site construction increases the burden of transportation and logistical costs – offsetting the proposed cost and schedule savings.

The third proposed solution is increasing wages to encourage more people to join the industry. However, increasing wages will cause project costs to increase. Furthermore, wages are sometimes driven by the current political climate in the US and other exogenous factors, such as the economic health of the market. In a recession, wages may tend to be low while companies correct for the economic downturn, and in a healthy market, wages can more freely move up. Others posit that this is not a solution. In a simulation study conducted by Kim et al. 2020, increasing the wages by fifty percent did not significantly impact the number of workers entering the field (Kim et al., 2020). This is the most used method in today’s market, but it has some way to go before being a proven solution.

The final proposed solution is increasing the funding for vocational programs for high school students. Hopefully, this will encourage young adults to enter the field and make them aware of the benefits of working in the construction industry. While many high schoolers are taught from a young age that the only way to be successful in life is to go to a university (Callanan et al., 2020) there are other paths to be explored. One such option is vocational programs leading to career paths in the construction industry. However, according to Callanan et al., only 6 percent of United States high school students were enrolled in a vocational program, while countries such as the United Kingdom, Germany, Netherlands, and Japan saw a much larger percentage (Callanan et al., 2020). Exploring and educating this optional career path in the United States would be prudent.

Literature Review

There are many previous studies of labor shortages in the construction industry. Productivity in construction is a popular topic among the sources reviewed for this study. The need for improved productivity was a guiding rationale in most of the past research on the topic of labor shortages. It was determined that the United States has the highest construction industry productivity numbers based on an analysis of four different countries: United States, United Kingdom, South Korea, and Japan (Lee et al., 2021). However, it is reasonable to assume that the labor shortage could soon be worsened by current legislation limiting or eliminating immigrant workers from the labor market. In the past, project costs due to immigration policy were increased by 12% (Golden et al., 2010). Moreover, recent metrics on skilled labor in the construction industry exhibit a continual increase year over year (ENR Skilled Labor Index, 2022). Despite the pandemic last year, the United States' construction spending hit an all-time high of just over $1.45 trillion (Beaudoin, 2021). The increased labor demand brought on by the increased construction spending is at risk because skilled labor is aging out of the currently available workforce. The average age of construction workers surpassed the average age of the United States labor force for the first time ever in 2017, meaning more construction workers are retiring than are entering the workforce (Sokas et al., 2019). The lack of junior tradespeople entering the workforce can be attributed to a limited understanding of the opportunities that are available within the industry (Callanan et al., 2020). With the lack of a qualified workforce, the improvements in the cost, time, and quality of ongoing projects are in jeopardy.

Currently, the solution to this problem is increasing training to develop more skilled laborers. According to Tam et al. (2021), creating more training opportunities, including workshop programs, leads to increased worker productivity that can limit the labor shortage significantly. Furthermore, Kim et al. (2020) claim that a ten-fold increase in the training rate of laborers decreased overall labor shortages by 85%. While a ten-fold increase might be hard for some companies to absorb, Podder et al. (2022) claim that the training can be expedited by using current technologies, such as virtual reality, to simulate real-world tasks that will make workers more productive in less time than traditional on-the-job training. This proves that technology is already making a significant impact in the construction industry, and there are many other exciting technological advancements that are currently being used and developed.

The articles researched suggest that the most predominant technological advancements today are the use of offsite construction and the use of robotics. Saad et al. (2021), states that offsite construction has vastly increased construction productivity for the companies and projects that have adopted it, however, few companies have used it to its full potential (. As promising as offsite construction is, it can still be improved. Brissi et al. (2022) found that using robotics to produce and assemble modular buildings can reduce the amount of labor required and increase overall productivity even further. These articles provided many great findings considered in this research, however, the collected literature had research gaps that need to be addressed by future research.

The most common issue between all the articles is that the researchers did not have the time or resources to cover all the potential factors of their given topic. The construction labor shortage is a large and complex topic and cannot be covered by a single research group. Brissi et al., Lee et al., and Saad et al. all stated in their respective works that the topics covered were too wide to cover all aspects that could impact their research. Also, most of the research studies were conducted at the height of the COVID pandemic. Additionally, the recent research published could have skewed data because of the volatility of the construction market during the pandemic. Lastly, researchers also noted that they did not have enough participants due to COVID restrictions. These are among the more common factors that limit the validity of the literature, however, there are more specific factors that need to be taken into consideration.

For example, Tam et al. (2021) focus on the perspective of project managers and contractors without considering the workers' point of view. Sokas et al. (2019) only cover the labor shortage faced by trade unions which only account for about twenty percent of the total labor force Callanan et al., 2020 faced limitations in their research regarding vocational programs in high schools because they found that students simply were not interested in joining the trades. Research on immigration's impact on the labor shortage conducted by Golden et al. was limited to only the Washington D.C. area, even though immigration issues are nationally pervasive (Golden et al., 2010). Lastly, the dynamic model proposed by Kim et al. was unable to disclose how different factors impacted the labor market within each trade, only the construction labor market as a whole was presented. Since these articles have limitations, they prepare the groundwork for future research regarding these topics.

The articles reviewed each provided their own ideas for how their work can be furthered by others in the field. Many of these suggestions consist of conducting similar studies but looking at different factors related to the respective issues. Also, COVID has been detrimental to the industry and surrounding research over the last couple of years. As the pandemic winds down, research should adapt to cover the labor market outside of the pandemic era. Offsite construction and robotics are both rapidly growing, and research will need to expand equally to stay on top of the most current technological advances. Overall, the labor market is a volatile subject, and innovative solutions need to be researched as quickly as new issues arise.

Methodology

The study used a survey method to determine construction professional's opinions on the current labor shortage, the causes, and their thoughts on the effectiveness of the proposed solutions. The survey was designed using an online survey and was categorized into three sections: demographics, current construction labor force conditions, and possible solutions. By using methods such as multiple choice, slider scale, 5-point Likert scale, and optional open-ended questions, the survey was able to give clear, accurate, quantitative, and qualitative results. When constructing the survey, the main objective was to develop strategies to help lessen the labor shortage's impact. By targeting superintendents and project managers of the construction industry, the survey sought to better understand the viewpoints of people that are dealing with the labor shortage daily. The first aim of the survey was to determine the demographic of the respondents. To do so, the respondents were asked whether they are currently in the construction industry and what sector of the industry they primarily work in. Next, the participants were asked their opinion on the severity of the current labor shortage. Following this, respondents were asked to answer questions on the four proposed solutions stated in the introduction. Finally, the respondents chose their overall most preferred solution out of the four factors of the study discussed in the introduction of this paper. The survey was analyzed and organized into a quantitative evaluation of the results.

Data Analysis and Results

The data was first gathered using an online survey and grouped into the following categories: Demographic Information, Background Information, Robotics, Off-site Construction, Increase Wages, Increase Funding to Vocational Programs in High Schools, and Overall Best Solution. The data was then consolidated into the following figures.

The survey was sent to construction industry professionals and received eighteen responses. Out of the eighteen responses, two individuals no longer worked in the construction industry, and therefore, these two individuals are others in this study, three worked primarily on industrial projects, and thirteen worked on commercial projects, as shown in Figure 1 (n=16).

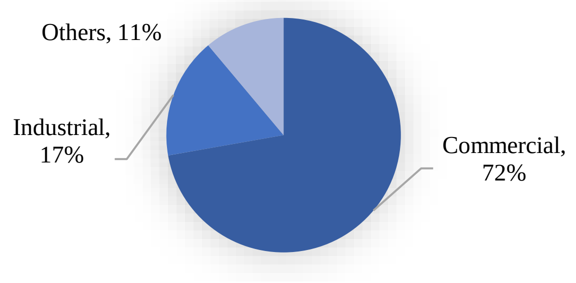

Figure 1. Demographics of the Respondents

Figure 2 is based on a question in the survey asking why respondents perceived there were inadequate junior workers entering the construction industry. Many respondents commented that the junior workforce was not aware of the opportunities in the construction industry. The other majority thought that they were aware of the opportunities but were not willing to work the hours or perform the labor that the industry demands.

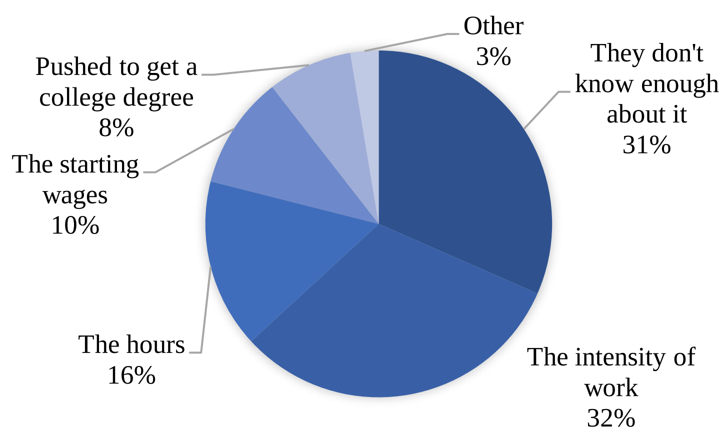

Figure 2. Detractors for Junior Workers Entering the Construction Industry

Figure 3 shows if the respondents agree that the solutions proposed in the introduction of this paper would be an effective treatment for the ongoing industry labor shortage. Most respondents would like to see an increase in funding for vocational programs in high schools that encourage young adults to enter the construction industry. However, most were unsure if technology and robotics would address the ongoing concerns for labor.

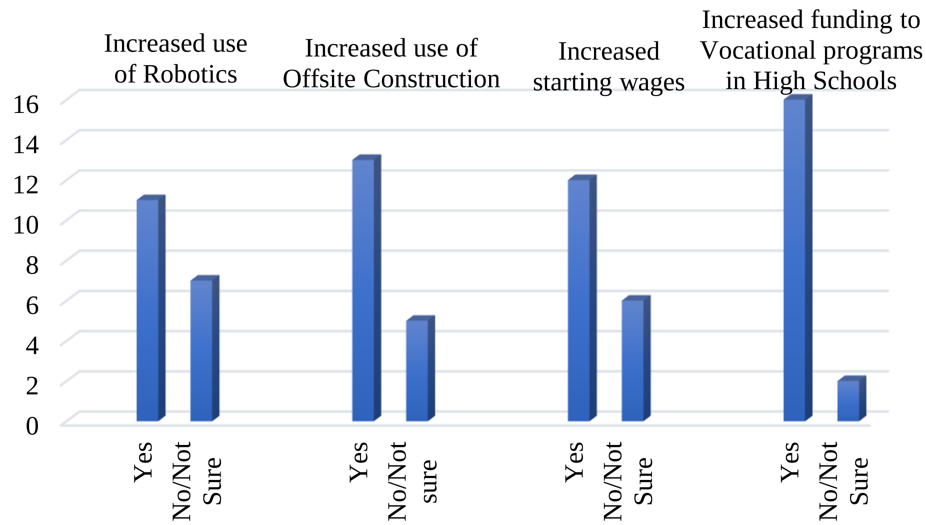

Figure 3. Industry Perceptions Regarding Proposed Workforce Solutions

The final question of the survey asked respondents which solution they felt would be the most helpful overall, as shown in Figure 4. The vast majority agree that increasing the funding for vocational programs in high schools is the best solution. Professionals in the field understand the urgency of the labor shortage, and an influx of young adults entering the field would provide the quickest and most economical solution for companies. Professionals are not confident that robotics or modular construction are the appropriate responses to the workforce problem.

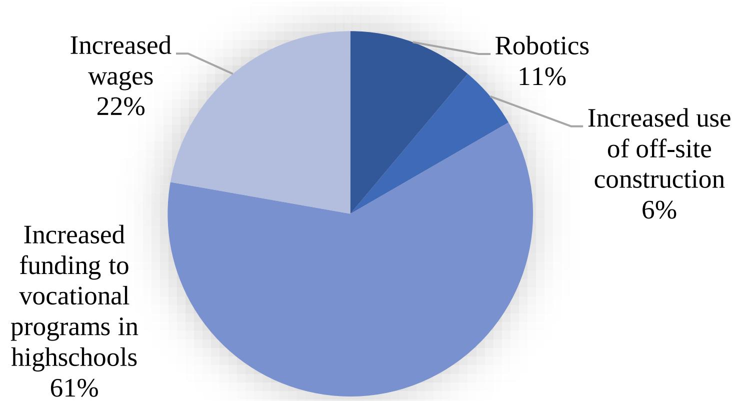

Figure 4. Ranking of Proposed Workforce Solutions (Industry's Perception)

Discussions

Respondents had the option to voice their own opinions regarding the proposed solutions. For robotics, respondents stated that they are unsure about the technology, and even if the technology were available, it would have to be looked after by people, therefore not solving the labor shortage. Survey participants criticized modular construction for still requiring labor and not being able to adapt to the uniqueness of each site. Respondents were against increasing wages because increasing wages does not increase skill. Therefore, productivity stays the same or decreases due to layoffs caused by cost overruns brought on by increased wages. The only comment made against vocational programs in high schools was that the young adults would not take the classes seriously or the classes would not be taught well. While both may be true, the idea is that young adults are exposed to the industry, and that should increase the incoming labor force. Table 1 includes a full offering of the respondent's open-ended responses.

Table 1: Open-Ended Responses

Proposed Solutions	**Open-Ended Responses**
Unsure Robotics in Construction	a. There are just some things that robots cannot do (at least not yet). b. Robotics are and will continue to grow in the industry. The field employees are and will receive special training to use this equipment. c. With every project being specialized and unique, there almost always needs to be human guidance and/or best judgment skills. d. Robotics seem like a good complement to human labor but shouldn't be embraced to replace human labor completely
Unsure about off-site construction	a. It takes labor to perform off-site construction. b. To grow a company and remain a top competitor, pre-fabrication is a must. It does shift field labor away from the job site, which always creates a more quality-controlled environment (better working conditions, less distractions, an increase in safety, and quicker turnaround), allowing less labor on-site with a faster construction schedule. This however allows a company to conduct more projects in which more labor is still needed. c. Don't have enough knowledge to form an informed opinion d. It cannot replace onsite because every site is different.
Unsure about increase in wages to lessen the labor shortage	a. Increased wages work sometimes, but if you constantly increase wages, someone has to pay for it. Increased wages usually lead to smaller crew size and more responsibility. b. Higher wages for the sake of it isn't the answer. There must be a correlation between pay, performance, skill, training, value-added and demand.
Unsure about increasing vocational	c. There will be people that take the classes to get credit. There will be people who take the classes and go into construction, and it will be nothing like the vocational courses that were taught.

programs in high school	d. It is due to the blanket term of "construction". It is due to every trade having its advantages and disadvantages.

Conclusion

The research shows that industry professionals lack confidence in a technological solution to the labor shortage problem. However, the industry is in such demand for labor that it will look at any option to help the workforce be more efficient. The leading solution that survey participants feel could benefit the most is increasing the funding for vocational programs in high schools. Thankfully, many other complimentary options are available to address the workforce shortage when considering vocational education and outreach. In the United States, national organizations such as Skills USA, the National Center for Construction Education and Research (NCCER), ACE Mentor, and the Construction Education Foundation of Georgia are actively working to address the workforce shortage issues. These programs focus on high school-aged children, and their impact has far-reaching implications for the industry. This research did not directly address these organizations, but based on the findings from the industry professionals, continuing or increasing the support of these organizations would mirror the desires of the professional that responded to this research.

The initial exploratory research findings are limited to industrial and commercial professionals, mainly in the Southeastern region of the United States. The data collected in this research only covers the opinions of professionals that could be reached with the electronic survey. Therefore, while it is difficult to generalize the findings in this research study to a larger population, it does provide a basis for applying the methodology to a larger and potentially targeted population. It is recommended that this study should be expanded to cover a broader portion of the country with a particular focus on increasing the response from trade disciplines that rely heavily on a skilled labor force.

References

Callanan, G., & Perri, D. (2020). Constructing construction careers: The case for the building trades. Education & Training (London), 62(3), 201-213. doi:10.1108/ET-06-2019-0117

ENR Skilled Labor Index, 2022, Index_History, assessed on 2022-12-20 https://www.enr.com/economics/historical_indices/Skilled_Labor_ Index_History

Erick Beaudoin. (2021). Construction continues to adapt amid increasing costs and labor shortages. The Secured Lender, 77(5), 30-33. Retrieved from https://search.ebscohost.com/login.aspx?direct=true&AuthType=ip,shib&db=lgs&AN=151117513&site=eds-live&scope=site&custid=ken1

Golden, S. K., & Skibniewski, M. J. (2010). Immigration and construction: Analysis of the impact of immigration on construction project costs. Journal of Management in Engineering, 26(4), 189-195. doi:10.1061/(ASCE)ME.1943-5479.0000021

Gusmao Brissi, S., Wong Chong, O., Debs, L., & Zhang, J. (2022). A review on the interactions of robotic systems and lean principles in offsite construction. Engineering, Construction, and Architectural Management, 29(1), 383-406. doi:10.1108/ECAM-10-2020-0809

Kim, S., Chang, S., & Castro-Lacouture, D. (2020). Dynamic modeling for analyzing impacts of skilled labor shortage on construction project management. Journal of Management in Engineering, 36(1) doi:10.1061/(ASCE)ME.1943-5479.0000720

Lee, C., & Won, J. (2021). Analysis of construction productivity based on construction duration per floor and per gross area, with identification of influential factors. Journal of Civil Engineering and Management, 27(3), 203-216. doi:10.3846/jcem.2021.14514

Podder, A., Gruchalla, K., Brunhart-Lupo, N., Pless, S., Sica, M., & Lacchin, P. (2022). Immersive industrialized construction environments for energy efficiency construction workforce. Frontiers in Virtual Reality, Vol3 Retrieved from https://doi.org/10.3389/frvir.2022.781170

Saad, S., Alaloul, W. S., Ammad, S., & Qureshi, A. H. (2021). A qualitative conceptual framework to tackle skill shortages in offsite construction industry: A scientometric approach. Engineering Construction and Architectural Management, doi:10.1108/ECAM-04-2021-0287

Sokas, R. K., Dong, X. S., & Cain, C. T. (2019). Building a sustainable construction workforce. International Journal of Environmental Research and Public Health, 16(21), 4202. doi:10.3390/ijerph16214202

Van Tam, N., Quoc Toan, N., Tuan Hai, D., & Le Dinh Quy, N. (2021). Critical factors affecting construction labor productivity: A comparison between perceptions of project managers and contractors. Cogent Business & Management, 8(1), 1-17. doi:10.1080/23311975.2020.1863303

Why are tradeswomen leaving the construction industry: An Exploratory Study

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The construction industry in the United States is currently undergoing historic shortage of skilled workforce. Several research studies have suggested to attract, recruit, and retain women in construction trades to address some of the workforce shortages in the future and also to improve jobsite productivity. Despite undertaking efforts in this direction to improve recruitment and retention of women in trades, it is observed that several women either left or considered leaving construction trades at some point in their careers. Previous studies focused on issues specific to women in administrative, managerial and leadership roles, however there is very limited knowledge relevant to issues of tradeswomen. This study exclusively focuses on tradeswomen and investigates the causes that influences tradeswomen to leave the construction industry with an intent to develop recommendations to improve their retention. To achieve the objectives, this study conducted twelve qualitative interviews with tradeswomen working in a variety of trades. The study identified important factors such as male dominant culture, inadequate attention from employers regarding tradeswomen issues, workplace and sexual harassment, discrimination such as pay imbalances, improper facilities, and misfit PPE Furthermore, recommendations for employers and industry organization were provided to improve tradeswomen retention. Understanding tradeswomen challenges helps improve their retention thereby improving the diversity in construction industry and contributes to the success of tradeswomen.
Key Words: women in construction, tradeswomen challenges.

Introduction

The construction industry in the U.S. employs around 10.6 million people, of which under 10% are women across all roles including administration, human resources, marketing positions and just under 3% are roles that include tradeswomen (NAWIC, 2018). According to a Bureau of Labor Statistics

(BLS) (2017) report, women represent 6.2% of painters, 3% of electricians, 2.1% of carpenters, and 1.7% of roofers in the construction trades. This makes construction trades one of the heavily male dominated of all positions within construction, and this needs to change to address the compounding skilled workforce shortages (Sedey, 2018) in the U.S. A recent data published in 2022 reported that construction industry saw an increase of women participation, as women constitute currently about 14% of the construction workforce, and the same report estimates that only a third of them are in the trades, indicating a single digit percentage (about 4%) of women working in the construction trades (Bloomberg, 2022; Goldenson, 2022). This indicates that despite the increase of women participation in construction industry in the recent years, it still remains that participation of women in trades must improve considerably. Additionally, a research study by Galea et al. (2015) indicated that lack of enough women participation in the construction industry, especially in trades resulted in worsening the skilled workforce shortages in the construction sector globally. Concurrently, several studies indicate the success of high school recruitment and other programs that have been initiated in the last few years to attract women into construction (Perrenoud et al, 2020) as the number of women that are entering the construction industry is on rise (Hebert, 2020). Despite the increase in number of women entering the construction industry, the industry still has single digit percentage of women in trades, because several tradeswomen either left or considering leaving construction workforce (Maurer, 2021). This emphasizes the important aspect of retaining women in the construction industry. To improve the retention of women in construction, it is important to identify the reasons that influence women to leave the construction industry and develop recommendations to address those challenges. Some studies identified reasons for women leaving construction sector, and those studies focused on women working in administrative, engineering, and executive roles. Nevertheless, it is important to focus on women in trades to address the historic skilled workforce shortages currently faced by the construction industry. There's very limited research focusing on challenges of construction tradeswomen, and strategies to improve retention of tradeswomen. Therefore, the purpose of this study is to focus exclusively on the issues of construction tradeswomen and develop recommendations to improve their retention within the construction trades.

Literature Review

The role of women in construction has recently drawn attention on a global scale. According to the literature, numerous studies have investigated issues including gender inequity, male dominance, entry obstacles for women into the construction business, difficulties for women in advancing their careers, and recruiting and engaging women in the field (Aboagye-Nimo et al., 2019; English & Jeune, 2012). Some issues include dealing with career gaps and breaks in employment due to family commitments or work-life balance issues (Aboagye-Nimo et al., 2019), culture of presenteeism on construction sites, and unfriendly family policies (Cabrera, 2009) by construction employers. The studies focused in the U.S. informed women in the construction industry face issues such as work-life balance, male domination, unfair impression of women's abilities, delayed career advancement, socio-cultural concerns (Azhar & Griffin, 2014), aggressive conflict filler culture within the construction industry (Hatipkarasulu & Ross, 2011). Lack of knowledge and a negative perception of the field, greater educational requirements, difficulties in finding qualified candidates, sexist attitudes, cultural restrictions, and family obligations are the main barriers that prevent women from entering the construction profession (Fielden et al., 2000). These existing studies have focused on women participation in the construction industry in certain positions after completion of their higher education in roles such as project engineer and above. However, women in the construction industry also work as tradeswomen and the challenges faced by tradeswomen were not paid enough attention in the literature. Dabke (2005) identified that women in construction trades are satisfied with the nature of work, however pay, benefits and job security offered to them is not satisfactory when compared to their male counterparts. A recent survey by institute for women's policy research conducted in early 2021 reported that 44.4% of the tradeswomen respondents working in the construction industry either left or seriously considered leaving the construction industry (IWPR, 2021). A regional report from the New York Construction Industry workforce reported concerning issues specific to loss of women from its construction workforce, indicating that almost 2 percentage points of tradeswomen working in the New York construction industry left and moved to other industries for employment (Construction Dive, 2016). Studies by large construction firms indicated the need to stop the flow of skilled tradeswomen out of construction industry (Naoum et al, 2020) to ensure the construction industry has a balanced and diverse workforce that is critical for the success of the industry. Therefore, it is important to understand the challenges the tradeswomen in the construction sector are facing and understand the reasons that influence them to leave the construction industry. This study bridges the gap by performing a qualitative study to explore the challenges faced by tradeswomen, understand success factors that influence retention of construction tradeswomen and further develop relevant recommendations. This will help construction firms, trade organizations, unions and policy makers determine relevant strategies to retain construction tradeswomen. During a time in which the greatest challenge U.S. industry faces is the acute shortage of skilled workforce (Hoover et al. 2016), it is imperative that actively addressing the tradeswomen retention issues can fill the increasing gap of qualified workforce needed in the construction industry.

Research Objectives and Scope

The purpose of this preliminary exploratory study is to review literature on women in construction trades and qualitatively identify the challenges faced by them, causes that influence them to leave construction industry and to develop strategies that improve retention of the understudied and underserved women population within the construction trades. The objectives are as follows: (1) determine the factors that influence women in trades to leave the construction industry (2) determine and develop strategies that help retention of women in construction trades. Through accomplishing this research objective, the authors aim to stimulate the interest of researchers across the globe and their engagement in research related to development and success of construction tradeswomen. Such research is essential not only for successful tradeswomen careers but also to inform public policy that is relevant to addressing the skilled construction workforce shortages.

Research Methodology

A qualitative research approach was selected for this study, and the data were collected through a series of semi-structured virtual or phone interviews that also focused on additional follow up questions with tradeswomen that are currently working in the construction industry and have considered leaving the construction industry at some point in their career. The authors designed the study around an in-depth literature review and conducted semi-structured phone interviews with tradeswomen from across the U. S. Building from the information collected in the literature review, the next phase in the research was developing a qualitative interview protocol that focuses on identifying tradeswomen challenges and recommendations for contractors to ensure success of tradeswomen in the construction industry. Prior to scheduling the qualitative interview, a survey questionnaire was sent to the participants to capture basic information such as name, background trade (drywall, plumbing, etc.), sector (commercial, residential, etc.), position (apprentice, journey level, superintendent etc.), years of experience, and other demographic information. The open-ended semi structured interview questions mainly focused on challenges faced by tradeswomen that influenced them to leave the construction industry, as shown in Table 1. The development of interview questions followed DiCicco-Bloom and Crabtree’s (2006) recommendations to include experience/behavior questions, and opinion/values questions. To recruit participants for this study, the authors adopted a snowballing sampling approach, wherein the authors reached out to few known tradeswomen that are working in the construction trades, initially extending an invitation to participate in the research. For each interviewee that accepted the opportunity to participate, they were asked for further contacts and introductions. This led introductions to 30+ construction tradeswomen that wanted to participate in this research and voice their challenges. However, due to time, location and schedule constraints, the authors selected 12 of them to be a part of the interviews for this study based on the information gathered from the initial demographic survey questionnaire. The criteria adopted by the authors to select potential participants is as follows:

1) Trades woman currently employed in the construction industry (or)
2) A minimum of six months experience in the construction trades
3) Willingness to participate in this study

The participants once selected, were sent emails containing the interview protocol and consent letter explaining the aims of this research and requesting their availability for the phone interview. The interviews were recorded with permission from the participants and transcribed for accuracy. The purpose of using a semi-structured interview approach was to initiate each interview with a set of open-ended questions that would lead to a thoughtful discussion and the flexibility to pursue appropriate follow-up and clarification questions regarding individual participant response. This gave the authors an opportunity to explore the respondent's perceptions and opinions regarding the challenges participants faced, and recommendations they have for employers and their men colleagues to provide a safe workplace, ensure success of women in trades such that women don't leave the construction industry.

Table 1
Open-Ended Interview questionnaire
Challenges as women working in the trades:
1) What challenges (personal, professional, workplace, etc.) do you face being a woman working in the trades? 2) How often the facilities (such as women only toilets) provided at the work site are women friendly? 3) Do you feel safe and secure being at the jobsite with other men?
Factors for leaving and recommendations:
1) Have you ever considered leaving the construction industry? Why? Why not? 2) What were/are the main reasons for leaving/considering leaving the construction trades? 3) What helped you feel comfortable / what do you think will help make you feel comfortable to continue working in the construction trades? 4) What do you think would be most helpful to increase the number of women in the trades? 5) Is there anything else you would like to share with me about your challenges being in the construction trades as woman? 6) Do you have any recommendations for employers/policy makers regarding women in trades?

The analysis primarily focused on identifying different themes relevant to the factors that influenced tradeswomen to either leave or consider leaving the construction industry. Manual thematic coding was used by the researchers to analyze the collected data to identify patterns and themes in the qualitative responses (Gibbs, 2007). The distribution of interview participants is provided in Table 2, which is based on the responses provided by the participant in the survey questionnaire.

While twelve interviews may seem a small sample, according to Mason (2010), the size of the sample in qualitative research becomes irrelevant due to the fact that the value of the study is based on the quality of data. One of the primary reasons for recruiting these twelve respondents was their experience, and willingness to participate in the study. Implementing such a strategy, according to Simms and Rogers (2006), increases the richness of data due to the commitment of the interviewers.

Additionally, it is to be noted that this is a preliminary exploratory study for a larger mixed methods study that is to be expanded in the future.

Table 2

Interview participant information

Participant	**Status**	**Trade**	**Location**	**Sector**
Participant 1	Foreperson	Drywall	Colorado	Commercial
Participant 2	Apprentice	Sheet Metal	Arizona	Industrial
Participant 3	Journeyperson	Electrician	Colorado	Commercial
Participant 4	Superintendent	NA	Tennessee	Residential
Participant 5	Apprentice	Paint	Illinois	Residential
Participant 6	Apprentice	Drywall	Colorado	Commercial
Participant 7	Apprentice	Mason	Arizona	Commercial
Participant 8	Foreperson	Mason	Arizona	Commercial
Participant 9	Apprentice	Concrete	Colorado	Commercial
Participant 10	Apprentice	Concrete	Colorado	Commercial
Participant 11	Asst. Superintendent	NA	Colorado	Commercial
Participant 12	Journeyperson	Concrete	Colorado	Commercial

Results and Discussion

This study utilized qualitative interviews to obtain information regarding issues that influence tradeswomen to consider leaving construction industry and recommendations to improve retention of tradeswomen. The interviews were conducted via phone calls or video calls, with each interview on average taking between 40 and 60 minutes. Based on the responses provided by participants in this research, the challenges faced by tradeswomen are organized into three themes, namely: 1) Culture in the trades, 2) Discrimination, and 3) Harassment

Culture in the Trades

It is evidently clear from the interviews that the work culture in the lines of "being a woman in man's world" influences retention of women in the construction trades. All tradeswomen mentioned that most workers in the construction industry opine that construction trades are not meant for women. Participant 11, that started in the trades and rose to the level of assistant superintendent said,

> Throughout my career, I came across several men [working in the trades] tell me that I won't make it in the trades because, I'm a woman. I still made it,

indicating the closed mindset of male workers in construction trades. Adding to this, participant 4 said,

> The biggest challenge I have found is that many people think that women shouldn't be at the job site working in trades. Through the years, I have encountered workers, clients, engineers, and many other stakeholders saying, 'I'm surprised to see a woman in the field',

Furthermore, participant 5 said, "Once a client was at the jobsite. They, in a surprising tone asked me, 'Are you the one who painted this? How do you do it?' with a puzzled face."
This statement indicates that not just workers in the trades, but also other stakeholders in the construction consider that women do not belong in the trades. Other themes identified include leadership teams of the construction employers not paying attention to the biological needs of tradeswomen such as not providing changing rooms, or separate toilets. Expanding on this, talking about a specific project she worked on, participant 3 opined,

> There wasn't a changing room; either you change before you leave home, or you go back home dirty. When brought this to notice, the leadership did not care much about it. Maybe because they don't care or there were no women leadership in the company that could understand this.

Other theme identified is that the men in trades think that construction is their world, and women are meant to stay out of it as they only have to take care of family. Supporting this, participant 6 said, "I constantly hear men co-workers saying, 'How'd you think you can build, you can't', 'You can't work in a man's field', 'Cook food for your kids, you belong to the kitchen'." This indicates that the cultural thinking within the construction industry that "construction is only for men" needs to be changed, and employers must work towards developing strategies to create awareness that construction industry open for everyone.

Discrimination

Tradeswomen informed that they suffer from discrimination both by their co-workers and employers due to which they have considered leaving the industry at least once. Some quotes by the participants are provided below. Discrimination related themes identified in this study are presented in Table 3.

> A lot of times, I felt that 'I'm just a number. I'm just here because they needed a female on the job [for quotas].' – Participant 8
>
> Most PPE including fall protection harnesses, safety shoes, gloves, etc. are all too large for me [typically made for men], posing safety hazard. PPE for men is readily available, however, it took them several months to get the PPE [for women] that could fit me. – Participant 10
>
> My opinion and feedback were ignored; nevertheless, when a male co-worker expressed the same opinion on the same piece of work, he was appreciated – Participant 1

This indicates discrimination for trades women in several areas that are relevant to their workplace success ranging from valuing tradeswomen's work to providing PPE to them.

Table 3

Discrimination related issues experienced by construction tradeswomen

Lower pay than men	Male dominated attitude	Unfair performance evaluation
Perceived as incapable	Limited training opportunities	Limited growth/leadership opportunities
Not being respected	Unequal recognition when compared to men	Jobsite facilities not inclusive for women (toilets, etc.)
Poor working conditions for women	Feels excluded in social conversations at workplace	Lack of women role models
Recruitment bias		

Harassment

All participants in this study informed that they experienced touching, comments and gestures from their male co-workers and supervisors, which is one the most pressing reasons for them to leave or considering leaving the construction industry. An apprentice who is working in the trades for 3 years, participant 7 mentioned,

> A male coworker whom I trust very much groped me one day. Another day, a group of male workers started making comments such as What can two ti** do great at the job that a group of horse can't do'. I started writing down all harassment I went through at work in the last two years, and I think I can publish a 300-page book now,

indicating the severity of workplace sexual harassment, the tradeswomen go through every day. Furthermore, other tradeswomen said,

> They [men at jobsites] call me 'babe', despite telling not to do so – Participant 7
> They [men at job sites] keep staring, and eventually hit on me – Participant 9
> I have men co-workers that told me I need to work out to be in shape, asked me wear more make up. Some wanted to know my sexual life – Participant 6

A forewoman working in the trades for several years further mentioned that the harassment scenario in the trades has never changed, participant 1, "I have been working in the trades for more than 15 years, and we are still dealing with the problems like harassment we had back then." When asked the reasons for not taking this to the notice of employers, most women participants mentioned they fear losing their jobs, making them reluctant to report harassment issues. This indicates that harassment is widely prevalent across construction trades, and it is not being reported enough. Employers must pay enough attention to this and create stringent workplace policies that curtail future harassment incidents.

Recommendations

The following are some recommendations for construction employers, policy makers, and unions to improve retention of tradeswomen.

1) Create an inclusive workplace and organizational culture that supports growth and success of tradeswomen. Create construction industry specific toolkits, company specific workplace toolkits, resources (e.g., women mentors), and advise to ensure tradeswomen have welcoming environment that supports their careers.
2) Create awareness and training for men working across all roles within the construction industry about inclusivity and best practices for ensuing a safe workplace for tradeswomen. It is important to provide continuous training (not just one training) to bring in the cultural shift required within the construction industry. This results in creating a team relationship where workers will support each other if a client or co-worker says something offensive to tradeswomen. Develop no tolerance policy against workplace and sexual harassment.
3) Encourage and provide opportunities for women to take up leadership roles within the construction industry. This helps the leadership understand issues of tradeswomen and develop unique ways to support them. Additionally, women in leadership roles act as role models that could inspire tradeswomen.
4) Discrimination in all forms must be eradicated. The construction companies should work towards tackling pay imbalances between men and women in trades. Employers have a responsibility to ensure trades women's fundamental requirements are met, which includes everything from providing appropriate toilet facilities to providing personal protection equipment that fits properly.
5) Community-building efforts and supportive policies from unions and industry organizations is also key to tradeswomen success in the construction industry. Creating women focused committees at the unions, women-focused pre-apprenticeship programs, tradeswomen support groups, etc. provides confidence to tradeswomen that could increase their retention.

Conclusion

The purpose of this research was to identify the factors that influence construction tradeswomen to either leave or consider leaving construction industry. A total of 12 interviews were conducted with tradeswomen who have considered leaving construction industry at some point in their careers. The study identified important factors such as male dominant culture, inadequate attention from employers regarding tradeswomen issues, workplace and sexual harassment, discrimination such as pay imbalances, improper facilities, and misfit PPE. The study also suggested recommendations that include creating inclusive workplace and organizational culture, creating awareness to men co-workers, developing policies to eliminate discrimination in all forms, provide better workplace facilities for women, community building efforts, and promoting women to leadership roles. The limitations of this study include limited sample size, participants belonging to just four states, participants from only five trades, and exclusion of perspectives from other trades. It is important to note that this is an ongoing study that is a part of larger mixed methods study, and more interviews with tradeswomen from other trades and region are scheduled along with a questionnaire survey to capture perspectives from a larger group of respondents. Future research will explore impacts of tradeswomen issues on the workforce shortages and develops organizational framework to promote inclusive workplace for tradeswomen.

References

Aboagye-Nimo, E., Wood, H., & Collison, J. (2019). Complexity of women's modern-day challenges in construction. Engineering, Construction and Architectural Management, 0969-9988. doi:10.1108/ECAM-09-2018-0421

Azhar, S., & Griffin, M. K. (2014). Women in Construction: Successes, Challenges and Opportunities – A USACE Case Study. 50th ASC Annual International Conference Proceedings.

Bloomberg. (2022). Women Are Smashing the Construction Industry's Concrete Ceiling as Labor Shortages Leave a Void. Retrieved via https://www.bloomberg.com/news/articles/2022-08-16/construction-jobs-filled-by-women-in-record-numbers-amid-labor-shortage

BLS (US Bureau of Labor Statistics). 2017."Women in the labor force: A databook." Accessed via <https://www.bls.gov/opub/reports/womens-databook/2017/home.htm>

Cabrera, E. (2009). Fixing the leaky pipeline: five ways to retain female talent. People and Strategy, 32(1), 40-45

Construction Dive (2016). "NYC finds loss of women, minorities from construction workforce concerning" Retrieved from: < https://www.constructiondive.com/news/nyc-finds-loss-of-women-minorities-from-construction-workforce-concerning/414504/>

Dabke, S. S. (2005). Job satisfaction of women in construction trades (Doctoral dissertation, University of Cincinnati).

DiCicco-Bloom, B., & Crabtree, B. F. (2006). The qualitative research interviews. Medical Education, 40(4), 314-321. doi: https://doi.org/10.1111/j.1365-2929.2006.02418.x

English, J., & Jeune, K. L. (2012). Do Professional Women and Tradeswomen in the South African Construction Industry Share Common Employment Barriers despite Progressive Government Legislation? Journal Of Professional Issues in Engineering Education & Practice, 145-152.

Fielden, S. L., Davidson, M. J., Gale, A. W., & Davey, C. L. (2000). Women in construction: the untapped resource. Construction Management and Economics, 18(1), 113-121.

Galea, N., Powell, A., Loosemore, M., & Chappell, L. (2015). Designing robust and revisable policies for gender equality: Lessons from the Australian construction industry. Construction management and economics, 33(5-6), 375-389.

Gibbs, G. R. (2007). "Thematic coding and categorizing." Analyzing qualitative data, 703, 38-56.

Goldenson, S. (2022). Recruiting and Retaining Women in the Building Trades. Retrieved from: https://www.segalco.com/consulting-insights/recruiting-and-retaining-women-in-the-building-trades

Gurjao, S. 2011.Inclusivity: The changing role of women in the construction workforce. Berkshire, UK: Chartered Institute of Building.

Hatipkarasulu, Y., & Roff, E. S. (2011, April). Women in construction: An early historical perspective. In 47th ASC Annual International Conference Proceedings of Associated Schools of Construction (pp. 1-7).

Hebert, K. K., (2020). Number of Women in Construction Industry Increasing. Accessed via <https://www.ecmag.com/section/your-business/number-women-construction-industry-increasing>

IWPR (2021). "Discrimination, Harassment, and a Lack Of Respect Threaten to Drive Women Out of the Construction Industry" Retrieved from: <https://iwpr.org/media/press-releases/discrimination-harassment-and-a-lack-of-respect-threaten-to-drive-women-out-of-the-construction-industry-according-to-new-institute-for-womens-policy-research-iwpr-report/>

Mason, M. (2010, August). Sample size and saturation in PhD studies using qualitative interviews. In Forum qualitative Sozialforschung/Forum: qualitative social research (Vol. 11, No. 3).

Maurer, J. A., Choi, D., & Hur, H. (2021). Building a diverse engineering and construction industry: Public and private sector retention of women in the civil engineering workforce. Journal of Management in Engineering, 37(4), 04021028.

Naoum, S. G., J. Harris, J. Rizzuto, and C. Egbu. (2020). “Gender in the Construction Industry: Literature Review and Comparative Survey of Men’s and Women’s Perceptions in UK Construction Consultancies.” J. Manag. Eng., 36 (2). https://doi.org/10.1061/(ASCE)ME.1943-5479.0000731

NAWIC (2018). Statistics of Women in Construction. Retrieved from: https://www.nawic.org/statistics

Perrenoud, A. J., B. F. Bigelow, and E. M. Perkins. (2020). Advancing Women in Construction: Gender Differences in Attraction and Retention Factors with Managers in the Electrical Construction Industry. J. Manag. Eng., 36 (5). https://doi.org/10.1061/(ASCE)ME.1943-5479.0000808

Simms, C. and Rogers, B. (2006), “The significance of flexibility in improving return on property investment: the UK perspective”, Facilities, Vol. 24 Nos 3-4, pp. 106-119

Sedey Ray (2018). "The construction industry is heavily male-dominated, and that needs to change" Retrieved from: <https://www.dallasnews.com/opinion/commentary/2018/09/03/the-construction-industry-is-heavily-male-dominated-and-that-needs-to-change/>

Effect of Competency Grading in Statics and Mechanics of Materials Course on Student Grades in Follow-On Course

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Competency grading is a non-traditional grading style that focuses on the proficiency of the learner. It has been proven in other studies to be an alternative grading system that works well in technical courses and has a lot of benefits for both the student and the instructor. The results of the data analysis for this study indicate that the mean grade in the follow-on course entitled "Introduction to Concrete and Steel Design" is higher when competency grading is used in the prerequisite course "Statics and Mechanics of Materials" than when traditional grading is used. The competency grading style helped students be more successful in the follow-on course than students taught with a traditional grading style because of changes to both student and instructor behaviors. Lessons learned are also included for faculty interested in considering adopting competency grading in their courses.

Key Words: Statics, Mechanics of Materials, Competency Grading, Alternative Grading, Construction Management

Introduction

Students are commonly assessed and graded using traditional means – they are given assignments and tests, each is scored in some way, and those scores make up a course grade. Depending on the quantity and weighting of the assignments and tests, it is often possible for a student to do very poorly on one or more assessments and still pass the course. For example, if there were four exams, they could score 85%, 75%, 65%, and 55% and earn a C average, yet they did not pass half of the exams. They may have completely failed major concepts, but still manage to pass the course. Because of issues like this, students may be allowed to progress into follow-on courses, but there may be gaps in requisite knowledge needed for those later courses.

At Boise State University, many students passing the junior level construction management Statics and Mechanics of Materials course struggled to successfully use that content in one or more of the four follow-on courses. In response to this mismatch, traditional grading was replaced with one based on competency. Competency grading requires that students prove their ability to successfully complete well-defined skills in order to pass the course.

This paper provides details of competency grading from the literature, as well as how it is used in a Statics and Mechanics of Materials course, provides an examination as to whether students that experienced competency grading were more successful in one follow-on course entitled “Introduction to Concrete and Steel Design” than students with traditional grading, and provides lessons learned for other faculty interested in trying this alternative grading method.

Competency Grading in the Literature

This paper will use the term Competency Grading, but it is relevant to note that there are many different names for non-traditional grading methods that focus on the proficiency of the learner, such as Standards Based Grading, Specifications Grading, Criteria Grading, Competency Grading, and Mastery Grading. There are small differences in what each of these names actually means (Nilson, 2015; Sadler, 2005; Townsley & Schmid, 2020), but the intent of all is similar – to ensure that students are evaluated on specific, clearly identified objectives, and that they master those objectives in order to successfully complete a course. Unlike in typical traditional grading schemes, here, course grades are clearly connected to level of mastery of the course objectives; students are required to show a well-defined level of mastery in order to pass a course. These alternative grading methods also generally allow students to show improvement over the duration of the course by providing multiple opportunities to demonstrate mastery of a topic.

Evidence in the literature suggests that these methods improve student engagement, help students have a more thorough comprehension of course materials, and help establish and maintain a high level of academic quality (Buckmiller et al., 2017; Iamarino, 2014; Kulik, et al., 1990; Nilson, 2015; Toledo & Dubas, 2017). Students cannot learn something halfway, but instead must review feedback from the instructor and incorporate it into future work in order to be successful in the course.

The use of competency grading is not well-documented in Construction Management disciplines, but is used in some engineering disciplines, including the teaching of statics courses. For example, Crough (2017) found that students in a statics course with weaker academic preparation were found to perform better when a partial use of this style of grading was used, with no harm done to students with stronger academic preparation. Ritz et al (2020) found that students exposed to a partial use of mastery learning received higher final exam scores than other students. Both of these studies used grades on traditionally graded final exams completed by both the mastery- and traditionally-graded students as their point of comparison between the groups.

Structure of Competency Grading in Course

Competency grading in the Statics and Mechanics of Materials course described in this paper began with a list of course objectives, which look fairly traditional for a course such as this.

Course Learning Objectives:

1. Recall and apply equilibrium equations to force systems.
2. Graphically illustrate problems of statics and mechanics using free body diagrams.

3. Calculate loads and the effects of forces on beams, trusses, and other simple structures.
4. Calculate engineering material properties and use with published strength information to solve problems.
5. Solve problems involving stress and strain.
6. Calculate and draw shear and moment diagrams for simply loaded beams.
7. Calculate bending stress, shear stress, and deflection in simply loaded beams.

These objectives were then modified and clarified, in coordination with the instructors of the four follow-on courses, to create two lists of objectives for evaluation in the course. These lists specify individual tasks to demonstrate mastery of various items in the course. Level 1 objectives are those where mastery is considered necessary to pass this course. These objectives were formed based on input from the instructors of the follow-on courses as prerequisite knowledge needed for a student to be successful in their course. Students must successfully complete all twelve Level 1 objectives by the end of the semester to be eligible for a passing course grade. Level 2 objectives are a combination of more complex and, therefore, more difficult versions of Level 1 objectives, and also objectives that are not considered absolutely essential to master for a passing course grade, but are commonly found in statics and mechanics of materials courses. Level 2 objectives allow students to raise their grade beyond the minimum passing grade of C-.

Level 1 Objectives (mandatory to pass course):

1. Add vectors mathematically and draw a graphic representing all individual parts and their sum
2. Correctly draw a free-body diagram
3. Given a beam or truss with loadings, calculate reactions
4. Calculate tributary area loading
5. Calculate the centroid of a composite shape
6. Calculate the moment of inertia of a composite shape
7. Calculate and draw the shear diagram for a simply loaded beam
8. Calculate and draw the moment diagram for a simply loaded beam
9. Solve a simple stress/strain problem
10. Calculate bending stress for a simply loaded beam
11. Calculate shear stress for a simply loaded beam
12. Calculate the deflection in a simply loaded beam

Level 2 Objectives (not required to pass course but can raise a student's grade):

1. Calculate the resultant of a coplanar force system (may be concurrent, nonconcurrent, and/or parallel)
2. Calculate and draw the shear diagram for a more complicated simply loaded beam
3. Calculate and draw the moment diagram for a more complicated simply loaded beam
4. Solve a more complex stress/strain problem
5. Solve a friction-related statics problem
6. Given a truss, find the reactions and determine the forces in the members by method of joints
7. Given a truss, find the reactions and determine the forces in the members by method of sections

Student mastery of each individual objective is assessed through problems (a separate problem for each Level 1 and Level 2 objective) done during test days in class. See Figure 1 and Figure 2 for example test problems. Work on each problem is marked Pass or No Pass. A Pass for an individual objective would meet the following requirements:

- Proper set-up

- Correct use of diagrams, equations, and units
- Clear conceptual understanding
- Correct, complete, clear solution using correct method, though minor math errors are sometimes overlooked

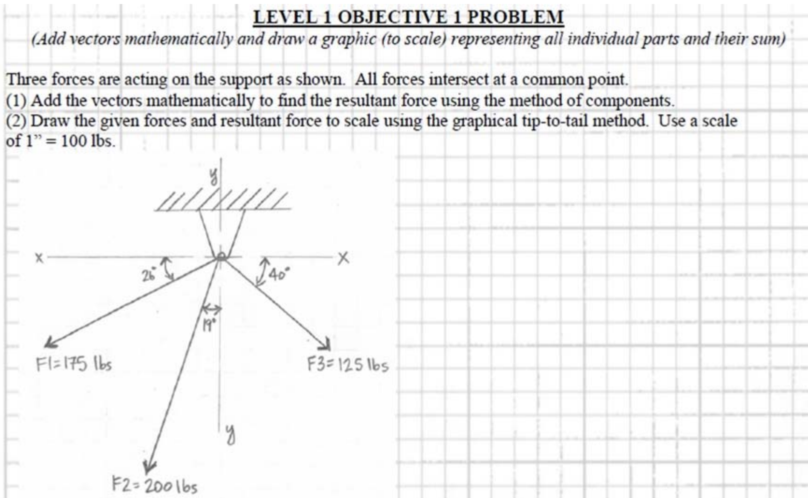

Figure 1. Example test problem

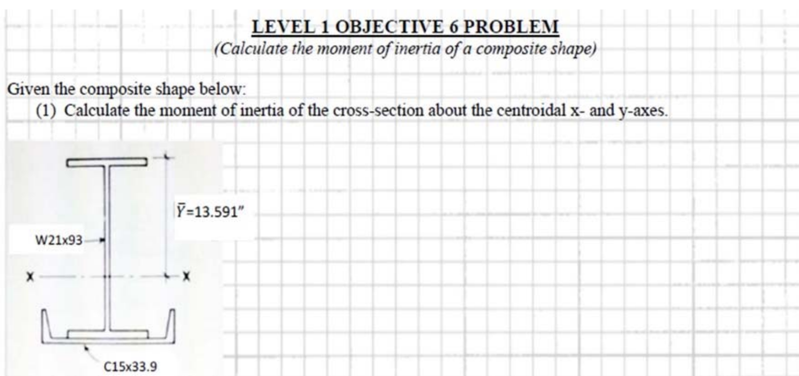

Figure 2. Example test problem

In this course there are five (5) class periods during the semester set aside as test days where students can attempt (or re-attempt) any of the Level 1 or Level 2 objective problems available at that point (they are made available after the topic/objective has been covered in class). Any objectives that are not passed on a given test day can be re-attempted with a similar problem on a later test day with no penalty, providing students multiple opportunities to demonstrate mastery on each objective throughout the semester. The final exam period is used only for re-attempting any objectives that students have not yet passed. Students are expected to master the concepts in each objective and not just get things partially correct. The grade earned in the course is based on how many objectives they demonstrate mastery of by the end of the course. A passing grade requires showing mastery of all Level 1 objectives and a student can receive higher grades by demonstrating mastery of Level 2 objectives. For example, a B grade in the course would require the student to pass all Level 1 objectives and four (4) Level 2 objectives. Practice problem and homework completion are also requirements for the course, but generally do not have a significant effect on the course grade unless the student chooses not to complete several of the practice problem sets or homework assignments.

Method

The research described in this paper was carried out with undergraduate students that were enrolled in a junior level construction management (CM) course entitled "Statics and Mechanics of Materials for Building Construction" course at Boise State University between Fall 2015 and Fall 2021 semesters (13 semesters total). A complete list of objectives covered in the course was included in the previous section. Those enrolled in the course are all CM majors and they have a minimum of one more year to complete their degree. The different semesters of the course were similar with respect to age, gender, and other demographics.

Three instructors of the Statics and Mechanics course are included in this research:

- Instructor 1 taught the course using traditional grading (2 semesters of student data)
- Instructor 2 (author) taught the course using competency grading (9 semesters of student data)
- Instructor 3 taught the course using competency grading (as established by the author) while the author was on sabbatical (2 semesters of student data)

The follow-on course that was evaluated is a senior level CM course entitled "Introduction to Concrete and Steel Design" using Spring 2016, 2018-2022 and Fall 2021 semesters (seven semesters total). It is also entirely CM majors and different semesters of the course were similar with respect to age, gender, and other demographics. This course is an introduction to the design of reinforced concrete and structural steel including sizing and design of beams, columns, and simple footings. It was taught by the same faculty member for all offerings evaluated here. Spring 2017 data for this course is omitted from this analysis because it was taught by a different instructor.

Grade data from students who completed both courses was analyzed to determine whether students that experienced competency grading in Statics and Mechanics had a higher mean course grade in the follow-on course than students with traditional grading. Because students do not necessarily follow from one course to a subsequent one as a cohort, this evaluation of success in the follow-on course is done only by instructor and method, and does not look specifically at semester that the course was taken. The hypothesis analyzed is as follows:

- *Null*: There is no difference in the mean course grade of students in the follow-on course due to the grading method used in the Statics and Mechanics of Materials course.
- *Alternate*: The mean grade of students in the follow-on course is higher for students that experienced the competency grading method in their Statics and Mechanics of Materials course than for those that experienced the traditional grading method.

Results and Discussion

As illustrated in Table 1, the overall pass rate (C- grade or higher) in Statics and Mechanics for the competency grading method is higher than for the traditional grading method. The competency grading method has also resulted in many fewer withdrawals of students mid-semester (6 withdrawals in 2 semesters of traditional grading vs 2 withdrawals in 11 semesters of competency grading). This is likely because they have the opportunity to continue to reattempt concepts and ultimately be successful in the course with this method even if they start the semester poorly. They also have the ability to clearly see what they need to achieve to pass the course, allowing them to make better decisions about their own success in the course.

Table 1

Grades from Statics and Mechanics course over 13 semesters

Instructor	Grading Method	# of Semesters in Study	Passed Course	D/F/W grade	Total # Enrolled	Total # Completed Course	% Passing (overall)
Instructor 1	Traditional	2	46	10	56	50	82.1%
Instructor 2 (Author)	Competency	9	237	29	266	264	89.1%
Instructor 3	Competency	2	46	1	47	47	97.9%

In Table 2, the follow-on course grades are shown by grading method from the Statics and Mechanics course. Students who took Statics and Mechanics using competency grading had a lower D/F rate than traditional graded students in the follow-on course (6.8% for competency vs 12.5% for traditional) and the percentage of A and B grades in the follow-on course was notably higher (54.3% vs 18.8%).

Table 2

Follow-on Course Grades based on Grading Method of Statics and Mechanics course

Grading Method in Statics Course	% Passing Follow-on Course	% A Grades	% B Grades	% C Grades	% D/F Grades	Mean Grade
Traditional	87.5%	6.3%	12.5%	68.8%	12.5%	2.063
Competency	93.2%	15.4%	38.9%	38.9%	6.8%	2.611

Grade data shown in Table 2 was transformed from letter grades to numerical ones where A = 4, B = 3, C = 2, D = 1, and F = 0. Any pluses or minuses included in student grades were ignored (for example, an A- grade was counted as an A grade for data analysis). A one-tailed t-test of the data comparing the mean grades of students from the two grading methods found that students completing the competency graded prerequisite course had a higher mean grade than the students completing the traditionally graded course (mean of 2.611 vs. 2.063) with a statistical significance of $p=0.012$. In other words, the mean grade for students who had Statics and Mechanics using the competency grading method was about one-half letter grade higher in the follow-on course than the students who had the traditional grading method.

Students Are Better Prepared

Students that pass the follow-on course are receiving higher course grades overall when competency grading is used in the prerequisite course than when traditional grading is used and the statistical analysis discussed previously supports this. There are two primary reasons why students are better prepared to be successful in the follow-on course: (1) student behavior and (2) instructor behavior in the Statics and Mechanics course.

Student behavior is different in a competency-graded course when compared with a traditional-graded course. In general, the author has seen increased engagement from students regarding the course content. Students discover that they must actually review feedback received on homework and exams, as they have to keep attempting an objective until they pass it. They cannot just skip over a topic if it is a Level 1 objective. Students interested in higher grades work even harder because they must master topics that are more difficult.

Because they do not receive scores for each objective, only a Pass or No Pass, students also become much less focused on their grades and more focused on learning and understanding each topic, including all of its subtleties, in order to pass each objective. Competency grading is ideal to help students develop a growth mindset, where a student believes their intelligence is not fixed, but can be developed, and also helps students focus more on the actual learning process which includes hard work, trying new strategies, learning from setbacks, and getting input from others (Dweck, 2016). Having a growth mindset can help students be successful in many different realms, from difficult courses to handling difficult tasks or problems in their future careers.

There are a number of instructor behaviors that are also important to consider that make students better prepared due to competency grading. The instructor must be able to help students overcome their failures. Students are generally not used to alternative grading methods such as this and it does take them time to adapt. The instructor must help students understand concepts more fully and help them learn from their failures when they receive a No Pass on objectives. Sometimes the author feels more like a coach, building up students' confidence of that they CAN do this. The instructor may also need to adapt the schedule of the course (front-loading important concepts is best) to allow time for the learning process to occur and ensure that students have time to overcome any failures before the course is completed. Additionally, the instructor must be flexible and able to teach students in the moment, when they are actually ready to sort out their misconceptions on various topics, which is not always when the topic is initially taught during the course. In the Statics and Mechanics course described in this paper, a number of class sessions are reserved for questions on any topic up to that point in the course. This often turns into a series of mini-lectures with small groups of very engaged students, while other students work on practice problems focused on their own topics of weakness.

Limitations

As with any educational study of this sort, there are many limitations that should be identified. Three categories of limitations will be described here: continuous improvement of instruction, COVID, and the data collected.

Both the author teaching with the competency grading method and the instructor of the follow-on course made incremental changes over the time of this study to support continuous improvement in their teaching. These changes influence the success of students in both courses, hopefully in a positive way overall. Additionally, most instructors improve their teaching of a course simply by getting more comfortable with the material and the topics that students tend to struggle with. These small changes, over the large number of semesters of the study, may have influenced the results favorably.

Changes in teaching mode due to COVID also presents a weakness in the data analyzed in this study. Two and one-half semesters of the author's course (half of Spring 2020, Fall 2020, and Spring 2021) and one-half semester of the follow-on course (Spring 2020) were taught live, but remotely through

Zoom due to COVID. Testing was also done remotely and, due to the type of content being tested, it was necessary to rely on trusting that the student was not using unauthorized resources during each test. If this assumption was not true, a student's grade in the course may have been inflated beyond what they would have earned in a more traditional classroom setting. Additionally, faculty were encouraged to be more flexible with their students, particularly in terms of assessments, due to higher levels of stress from COVID and other outside circumstances (McMurtrie, 2020). All of these factors may have influenced the results, again, favoring the competency grading mode in the data analysis.

The data itself is also a limitation of this study. Data collected in an educational setting is tremendously complex and can be affected by many different variables (McKeachie, 1999), including aspects that are not intended to be part of a study, such as (in this work) student and instructor characteristics. Adding more data both from future competency-taught semesters and from past semesters of the traditionally-taught course would strengthen (or weaken) the conclusion that competency-based grading does better prepare students for a follow-on course. With more data, the analyses performed could also be more complex, reducing the effect of some of the potentially confounding variables such as the influence of COVID, and providing a clearer picture of the influence of competency grading on the follow-on course. Having more data may also indicate a way to predict students that are likely to be at risk of not passing the follow-on course so that additional support can be provided to them.

Lessons Learned

Faculty considering trying this method in their classroom should be aware of some advantages and challenges when using competency grading. The grading of exams is generally much quicker in competency grading because each problem is graded as Pass or No Pass, with no scores or partial credit. Also, students who are not interested in A or B grades in the course attempt only the Level 1 problems and leave the Level 2 problems blank, potentially reducing the amount of grading required. However, exam creation takes more work. Custom exams are prepared for each student, including only the objectives they have not yet passed. Additionally, because students can reattempt objectives, there is a need to prepare the same objective multiple times through semester. The additional preparation time can be reduced once a large bank of test questions has been created, but in the beginning, it can be more work.

Giving students multiple opportunities for demonstration of mastery helps students who are slow to catch on to concepts and/or have a bad test day. As long as they are able to master each concept by the end of the semester, they will be successful in the course. Some students see the requirement for proving mastery as a negative, however, and view this grading style as "horribly flawed" (actual quote from a course evaluation). They are used to getting things partially correct and earning enough credit to pass a course. The competency grading scheme does not accommodate that approach very well and it can be a significant adjustment for some students, particularly when they receive a No Pass on an objective for what they view as a very minor error, while the instructor grades it as a significant concept error. It is important that the instructor focus on feedback that helps a student to develop a growth mindset; they are capable of learning from their mistakes and improving over time.

In addition, changes to both student and instructor behavior that were discussed elsewhere in this paper are also important to acknowledge as adjustments that may need to be made if considering a transition from traditional to competency grading.

Conclusion

Competency grading has been proven in other studies to be an alternative grading system that works well in technical courses and has a lot of benefits for both the student and the instructor. The results of the data analysis for this study indicate that the mean grade in the follow-on course is higher when competency grading is used in the prerequisite course. Students taught using a competency grading style are more successful in a follow-on course than students taught with a traditional grading style.

References

Buckmiller, T., Peters, R., & Kruse, J. (2017). Questioning points and percentages: Standards-based grading (SBG) in higher education. *College Teaching*, *65*(4), 151-157.

Craugh, L. E. (2017, June). Adapted mastery grading for statics. In *2017 ASEE Annual Conference & Exposition*.

Dweck, C. (2016). What having a "growth mindset" actually means. *Harvard Business Review*, *13*(2), 2-5.

Iamarino, D. L. (2014). The benefits of standards-based grading: A critical evaluation of modern grading practices. *Current Issues in Education*, *17*(2).

Kulik, C. L. C., Kulik, J. A., & Bangert-Drowns, R. L. (1990). Effectiveness of mastery learning programs: A meta-analysis. *Review of educational research*, *60*(2), 265-299.

McKeachie, W. J. (1999). *Teaching tips: Strategies, research, and theory for college and university teachers* (10th ed.). Houghton, Mifflin Co.

McMurtrie, B. (2020, June 4). *What does trauma-informed teaching look like?* The Chronicle of Higher Education. https://www.chronicle.com/article/What-Does-Trauma-Informed/248917

Nilson, L. B. (2015). *Specifications grading: Restoring rigor, motivating students, and saving faculty time*. Stylus Publishing, LLC.

Ritz, H., Dimiduk, K., & van Paridon, A. (2020, June). Effect of mastery-graded exams on student outcomes in statics and mechanics of solids course. In *2020 ASEE Virtual Annual Conference Content Access*.

Sadler, D. R. (2005). Interpretations of criteria-based assessment and grading in higher education. *Assessment & Evaluation in Higher Education*, *30*(2), 175-194.

Toledo, S. & Dubas, J. M. (2017). A learner-centered grading method focused on reaching proficiency with course learning outcomes. *Journal of Chemical Education*, *94*(8), 1043-1050.

Townsley, M., & Schmid, D. (2020). Alternative grading practices: An entry point for faculty in competency-based education. *The Journal of Competency-Based Education*, *5*(3). https://doi.org/10.1002/cbe2.1219

Challenges in decarbonising space heating in the UK

Case Study

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Abstract

The British climate means that space heating is an important element of the national energy budget and is therefore a significant part of the challenge to meet the UK legal target of zero carbon by 2050. One of the solutions to this challenge is the widespread deployment of heat pumps to replace gas fuelled heating systems in buildings. Heat pumps are electrically driven and can be highly efficient. The increase in renewable sources of electricity has made electricity comparable to gas in terms of carbon intensity. However, this method of heating buildings places greater strain on the National Grid. This study examines a heat pump installation in an existing educational building previously heated by gas. Temperatures and heat outputs were logged for a typical space within the building for a defined period when weather conditions imposed a large load. Data indicated that the heat pump system coped with abnormally low outside temperatures, though further fine-tuning of controls and refinement of other services is necessary to limit the increase in electrical demand.

Key Words: Decarbonisation, space heating, heat pumps, national grid, energy monitoring.

Introduction

The UK government has set a legal target of reaching net zero carbon by 2050. Though this refers to the whole UK economy, an important element of this strategy is the energy involved in buildings and in particular, the energy required to provide heating. Heating accounts for 37% of UK carbon emissions (Catapult Energy Systems, 2022) of which 17% is for space heating, 4% is for hot water and 2% for cooking. Decarbonising UK heating is therefore a significant part of the net zero challenge. The Department for Business, Energy and Industrial strategy has identified heating as “arguably the most difficult of the major energy consuming sectors of the economy to decarbonise”. (2018). This paper considers one attempt to reduce carbon by replacing a fossil fuelled system

Net Zero for Operational Buildings

Part of the proposed decarbonisation strategies for UK heating systems is to eliminate the use of natural gas as a heating fuel. The Committee on Climate Change (CCC) predicts that, by 2050, all domestic heating will be provided by heat pumps (52%), district heating (42%), hydrogen (5%) and direct electric heating (1%). An electrically powered solution using heat pumps for heating appears to be the presently preferred option, particularly as modern (5^{th} generation) proposals for heat networks also involve heat pumps transferring energy from ambient loops. Although heat pumps are attractive because they can operate at high efficiencies (Coefficients of Performance), widespread use will place increasing demands on the electrical system. Crawley and Price (2022) have identified that “if most households start to use a heat pump, the “peak” winter electricity use grows to more than double the current peak winter demand”. Some work by the UK Energy Research Centre (Wilson, et al., 2018) examined UK gas and electricity demands during winter of 2017/18 (Figure 1). This illustrates that meeting heating demand by replacing gas with electrical power may reduce carbon emissions but will require careful consideration of its effect on UK electrical power supply.

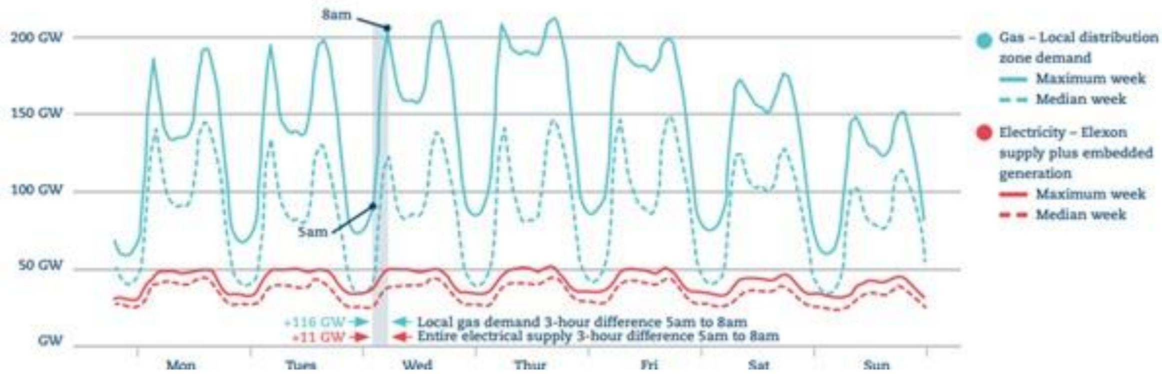

Figure 1 *Britain’s local gas demand and electrical system supply - median and maximum demand weeks (source: Wilson et al)*

The challenge of zero carbon by 2050 has generated a range of research projects by government industry, and academia. The Net Zero Industry Infrastructure Coalition has produced a report, which sets out three pathways (2022). These are: an electrification pathway involving widespread deployment of heat pumps combined with the roll out of electrical vehicles; a hydrogen pathway in which most homes are heated by hydrogen combustion; and a hybrid pathway where heat pumps are supported by biomethane-fuelled boilers. National grid has set out four credible pathways to achieve a fully decarbonised electricity system by 2050. (2022). Both studies have some general agreement but differ in terms of emphasis and policy. However, a theme that is consistent in all proposals, apart from the introduction of greater energy storage, is the critical need for improved energy efficiency.

Research Method

This study is an examination the decarbonisation of a heating system for an individual building. It is recognised that some of the individual characteristics for this installation may not apply elsewhere, however, a case study can provide some real -life context. This study observed parameters (internal temperatures, electricity use) which indicate if the replaced plant, not only reduces carbon emissions, but is also operationally effective. Further investigation of similar projects can contribute to greater expertise in this strategy.

Replacing Gas Boilers with Heat Pumps at Henry Cotton Building.

The Henry Cotton Building is part of the Liverpool John Moores University campus and is currently used for built environment and public health studies. Decarbonising the heating system for this building has been achieved by replacing gas-fired plant with electrically powered air source heat pumps. The original plant was rated at an output of 800 kW but has been replaced by heat pumps with a total output of 420 kW.

Air source heat pumps require more space than boiler plant as well access to fresh air. The reduced output has made this less of a space problem for designers. Another advantage in this case is that the original boilers were sized conservatively. Heat demand for this building was explored using dynamic simulation and revealed that satisfactory internal temperatures could have been achieved with smaller plant (Figure 2).

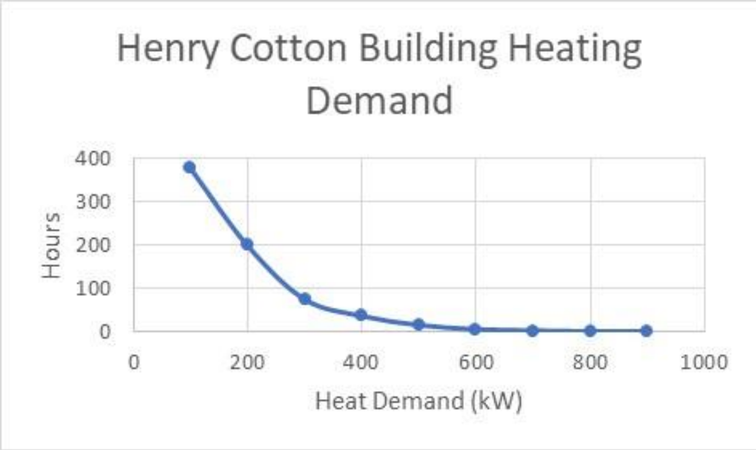

Figure 2 Heating demand Henry Cotton Building

Day (2021) considers that the relatively inexpensive cost of boilers and rules of thumb estimates has meant that historically, less emphasis has been placed on accurate sizing of boilers. Though this has, in the past, led to poorer efficiencies, increased capital costs and greater building areas and volume requirements, the original plant over-sizing has made heat pump installation easier. Images (Figure 3) of the original boiler plant and new heat pumps indicate the comparative space requirements.

Figure 3 Space requirements for boilers and air source heat pumps Henry Cotton

Heat Pump Performance

To determine the effectiveness of the replaced heating plant, the heat pumps should achieve similar indoor temperatures to those provided by the original system. For carbon reduction, the heat pump should achieve a Coefficient of Performance (COP) that provides 2.5 to 2.8 kW heat output for every kW of electrical input, depending on flow and outside air temperatures (Figure 4). The heat pump installation should also demonstrate elimination in gas usage for space heating and a reduction in carbon emissions.

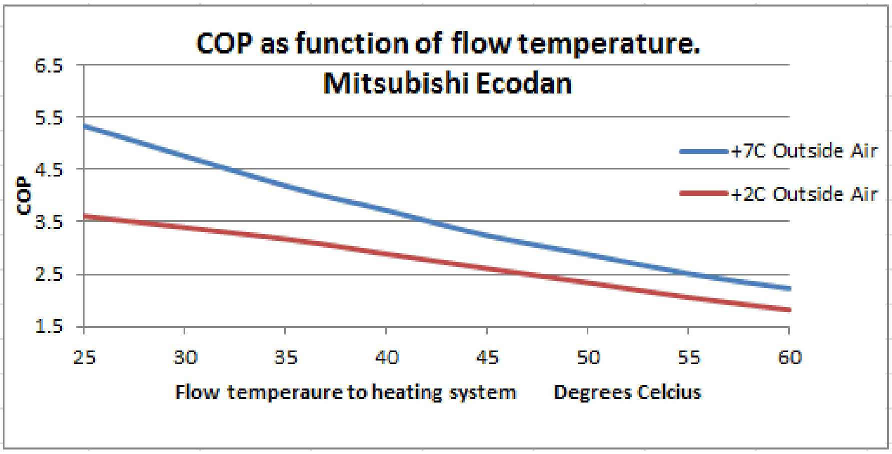

Figure 4 The relationship between heat pump flow temperature and outside air temperature (Source: CW Consulting)

An assessment of indoor conditions was made by selecting a typical space and monitoring indoor and radiator flow and return radiator temperatures over a period of seven days (9th to 15th December). This period represented a severe cold spell for the Liverpool area with consequent heat load for the Henry Cotton Building. A room temperature of around 25^0C (figure 5) was measured for all plant operational periods. Flow and return temperatures to radiators were steady at around 40 ^{0}C and 37^0C.

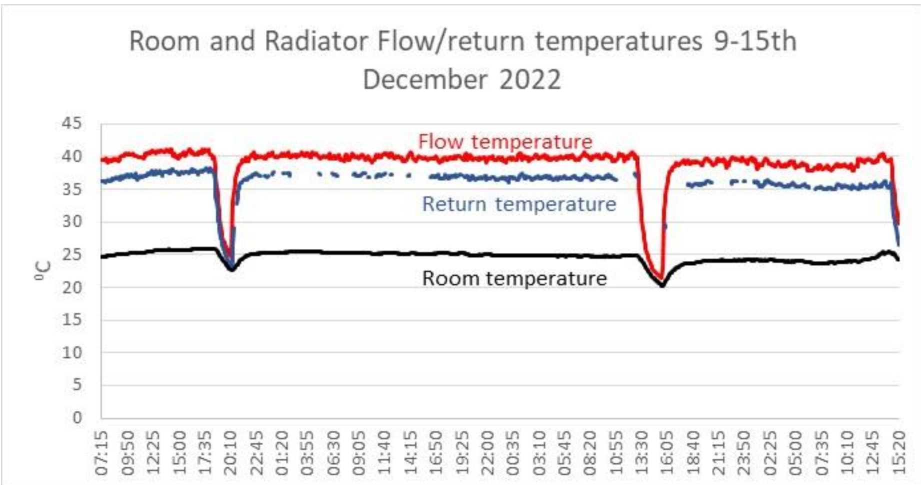

Figure 5 Room and radiator temperatures (Source: HOBO temperature monitor)

The campus building management system logged outside air temperature for the study period (Figure 6). Outside air hovered around freezing temperature for much of the period and dropped as low as -5^{0}C at night.

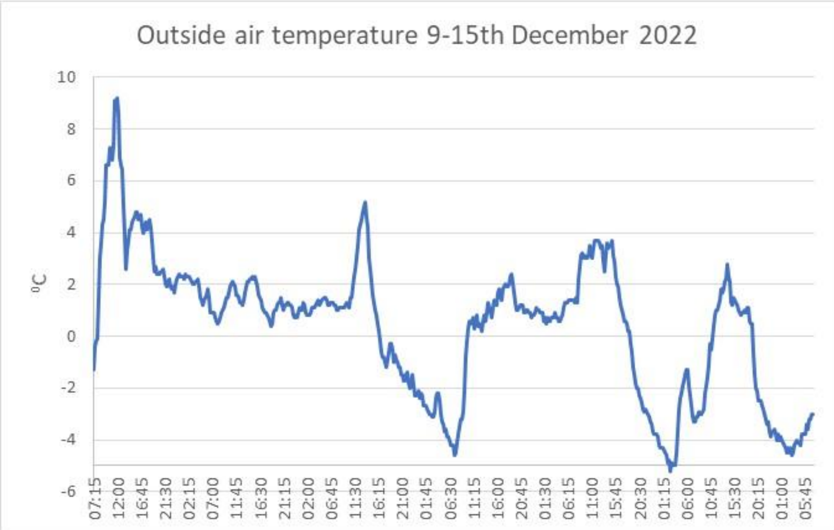

Figure 6 Outside air temperature in Liverpool (9th -15th December 2022) (Source: LJMU Campus BMS)

The campus building management system also logged heat pump flow temperature and heat delivered. The heat pump flow temperature averaged 54.5^{0}C (figure 7).

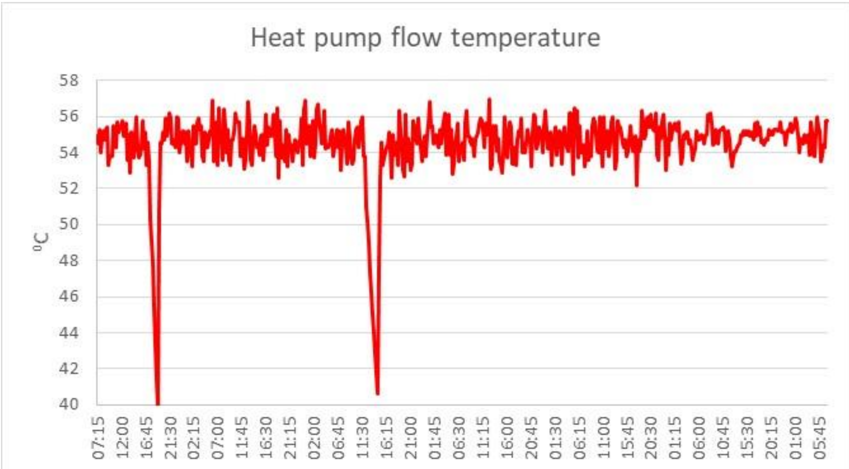

Figure 7 Heat pump flow temperature (9th to 15th September) (Source: LJMU Campus BMS)

The heat pumps delivered 23 509 kWh of heat energy and heat pump flow temperature averaged 54.5^{0}C. This figure is based on space heating to those areas heated by low pressure hot water radiators (classrooms and offices). Lecture theatre air conditioning plant was not used during this period.

Results and analysis

Room and radiator temperatures.

Low-pressure hot water heating plant in the UK has typically delivered hot water to radiators at around 80^0C, with a return temperature of 70^0C. A similar flow temperature for a heat pump system would have an adverse effect on the coefficient of performance and the design flow and return temperatures for Henry Cotton are 50^0C and 40^0C, which equates to a radiator surface temperature of approximately 45^0C. This lower radiator surface temperature would reduce heat output by around 54% ((Radiators, 2022)). To offset this reduction in heat output additional radiators were installed in rooms. Some over-sizing of the original installation may have assisted here.

Although the actual radiator flow/return temperatures indicate a reduction in radiator heat output of 65%, the monitored room temperature was around 25^0C. CIBSE recommend a comfort temperature for a teaching space of between 19 and 21^0C (2006). For this space, the system is over-performing. The additional radiators may contribute to this effect, but it is more likely that the heating controls require some fine-tuning.

Heat Pump Coefficient of Performance

The heat pump flow temperature for the study period has averaged 54.5^0C. This value is higher than the system design temperature (50^0C). The combination of a higher flow temperature and low outside temperatures will reduce the heat pump coefficient of performance. Manufacturer's information provides data for COP's and outside temperatures of between 2 and 7^0C but is not clear for lower outside temperatures. The average outside temperature for the study period was 0.4 ^{0}C.

From the theoretical COP thermodynamic equation (equation 1) for heat pumps and substituting flow and outside temperatures for condensing and evaporating temperatures, a comparison of theoretical COP's was estimated, At the logged operational conditions COP reduced by 9.7% compared to 2.5 at design condition.

$$COP_{heat\ pump} = \frac{Condensing\ temperature}{Condensing\ temperature - evaporating\ temperature} \quad \ldots(1)$$

Carbon Emissions

The heat pump system delivered 23 509 kWh (LJMU campus BMS) of heat energy to the Henry Cotton building during the week 9th to 15th December. If this level energy had been supplied by gas boilers at an efficiency of 90%, the primary fossil fuel energy input would have been (23 509/0.9) 26121 kWh. The Standard Assessment Procedure (SAP) (2019) carbon factor for natural gas is 210 g CO_2/kWh. Therefore, the carbon saved by eliminating gas boiler plant (26121* 0.21) is 5485.4 kg or 5.485 tonnes.

The electrical energy input, using a COP of 2.4 was (23 509/2.4) 9795.4 kWh. The SAP factor for electricity is 233 gCO_2/kWh. Therefore. the carbon emitted during the study period was (9795.4* 0.233) 2282 kg or 2.282 tonnes. The net saving in carbon emissions was (5.485-2.282) 3.203 tonnes.

Annual Gas and Electricity Use

The annual gas and electricity used at Henry Cotton for the year 19-22 is demonstrated in figure 8. Clearly, gas use has diminished considerably now that none is used for space heating. However, there is a corresponding increase in electricity demand. Though the carbon emissions trade off is positive, the increase in electricity use, if cumulative can have implications at grid level.

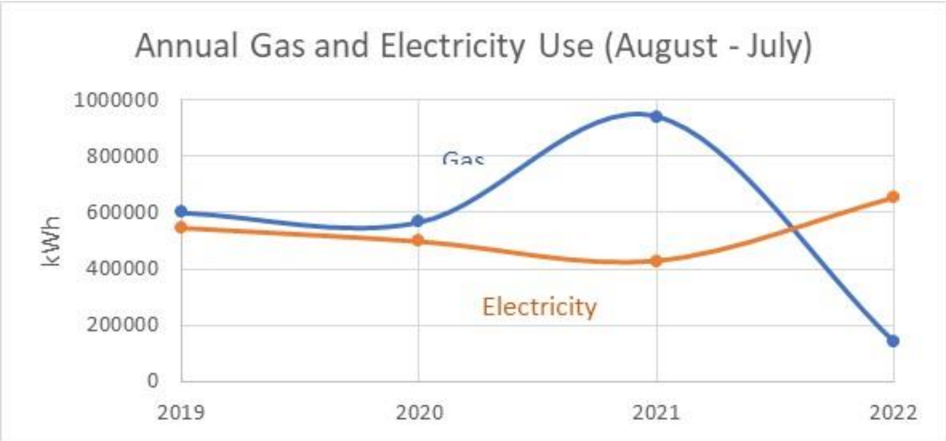

Figure 8 Annual Gas and Electricity (Source: LJMU Estates Dept.)

Conclusion

The monitored data for the study period suggests that the heat pump system effectively replaces the gas fired boiler plant by providing suitable internal temperatures and significantly reducing carbon emissions. Over a period of 7 days the heat pump system reduced carbon emissions from the Henry Cotton Building by over 3 tonnes, based on the UK Standard Assessment Procedure factors for carbon emissions.

The data in this examination has been obtained from recently installed monitoring equipment and the LJMU campus building management system. While both facilities are extremely informative, further cross-checking of data with utility bills, energy meters and meteorological information will be necessary.

Although the study looked at a period of high heat load, a deeper and longer monitoring exercise will be required to fully assess system performance. This exercise should also consider system control, occupant comfort, maintenance issues, potential refrigerant leakage, and running costs.

The increase in electrical energy demand contributes to the load on the National Grid so it also necessary to find further efficiencies. Lighting and office machinery are candidates for reductions where co-ordination with occupancy has some potential for energy saving. Improved motor speed control measures can reduce pumping energy. The limited monitoring for this study indicates some potential over-sizing of the original design and this could be explored to find other reductions in electrical demand.

References

Bennet, G. & Elwell, C., 2020. Effect of boiler oversizing on efficiency. *Building Services Engineering Research and Technology,* Vol 41(6), pp. 709-726.

Catapult Energy Systems, 2022. *How much does heating contribute to UK carbon emissions?.* [Online]
Available at: https://es.catapult.org.uk/guide/decarbonisation-heat/
[Accessed 12th September 2022].

CIBSE, 2006. *Environmental design CIBSE Guide A.* 7th ed. London: The Chartered Institute of Building Services Engineers.

CIBSE, 2021. *Electrification of buildings for net zero.* 1st ed. London: The Chartered Institute of Building Services Engineers.

Crawley, J. & James, P., 2022. *Heat pumps for UK homes: how will they be powered?.* [Online]
Available at: https://www.ucl.ac.uk/bartlett/energy/news/2022/feb/heat-pumps-uk-homes-how-will-they-be-powered
[Accessed 10th September 2022].

Day, T. et al., 2021. *Electrification of Buildings.* Ist ed. London: CIBSE.

Department for Business, Energy and Industrial Strategy, 2018. *Clean growth:Transforming Heating,* London: UK Government.

Engineers, C. W. C., 2022. *Crookes Walker Consulting Engineers.* Liverpool: Crookes Walker Consulting Engineers.

Government, U., 2019. *Standard Assessment Procedure,* Watford: Building Research Establishment.

Liverpool John Moores University Estates Depratment, 2022. *Gas and electricity consumption figures.* Liverpool: LJMU.

National Grid, 2022. *Future Energy Scenarios.* [Online]
Available at: https://www.nationalgrideso.com/future-energy/future-energy-scenarios
[Accessed 12th September 2022].

Net Zero Industry Infrastructure Coalition, 2022. *What we need to do and when : 3 roadmaps for decarbonising heat by 2050,* s.l.: Mott McDonald.

Radiators, S., 2022. *The Radiator Book.* Mexborough: Stelrad.

Wilson, G., Taylor, R. & Rowley, P., 2018. *Challenges for the decarbonisation of heat: local gas demand versus electricity supply,* London: UK Energy Research Council.

Online Education Efficacy in Construction

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The COVID-19 pandemic has had an enormous and long-term impact on education systems across the nation. Consequently, many colleges and universities adopted a verity of different instructional strategies and new policies to mitigate the effects of this transition on academic achievement, student learning, and emotional well-being. This instantaneous change to the new pedagogical models was likely to impact both students and instructors. In this study, a survey was conducted to analyze the effectiveness of adopting innovative teaching approaches in online and hybrid frameworks on students' engagement, achievement, and attainment at Northern Kentucky University. Two statistical t-test and ANOVA test were performed to compare the results and demonstrate the significant differences between groups of data. In addition, the survey responses were correlated with grades in the subsequent semesters to determine efficacy. The result shows that incorporating active and interactive learning strategies can improve online learning experience of students. The responses indicate that introductory level and lab-based courses may benefit more from aforementioned strategies.

Key Words: Construction Education, Online Education Efficacy, COVID-19

Introduction and Background

For the first-year and second year students, moving to online learning was shown to be the worst outcome of the initial Covid-19 transition in Spring 2020 (Karimi et al., 2021). Their junior and senior counterparts, however, felt the social distancing was the worst outcome (Karimi et al., 2021). The faculty sought to create an environment of learning which would overcome the different concerns of both the lower and upper-level students.

Including inclusivity in an online classroom can focus on accessibility (Harris et al., 2020), which can be defined in multiple ways. Construction, Engineering and Engineering Technology students have identified accessibility in an online classroom as a concern, although it was not well-defined (Mosier et al., 2022). While accessibility is often associated with inclusivity, it may also be as simple as access to online content (Harris et al., 2020) or access to faculty outside of the online classroom. Students report a preference for a combination of synchronous and asynchronous over either one used solely as a delivery method (Karimi et al., 2022).

An active learning pedagogy and online learning do not have to be mutually inclusive. Rather, it is incumbent on the faculty to identify create active learning opportunities (Harris et al., 2020). Active learning pedagogies are generally considered to be student-centered (Liszka, 2013). Active learning pedagogy includes many sub-categories, like problem-based learning (PBL), inquiry-based learning (IBL), collaborative and cooperative learning and case studies (Liszka, 2013). One of the aspects of student-centered pedagogies is students working together, collaborating, to find solutions. Group projects can create opportunities for interactions outside of an online classroom. Group work does not necessarily increase satisfaction in an online course as scheduling face to face meetings between students can still be difficult (Lee et al., 2016).

While self-efficacy includes “technology, learning, and social interaction” (Shen et al., 2013). Technology does not necessarily promote student collaboration. As collaboration is related to self-efficacy (Stump et al., 2011), assignments may focus on group laboratory exercises or projects. Outside of the classroom, students may seek collaborate learning opportunities, irrespective of any effect it may have on grades (Stump et al., 2011). In pre-pandemic online courses, collaborative learning was utilized to encourage course participation through student perception of responsibility to each other based on mutual trust (Stoytcheva, 2018).

Based on the results of the initial move to online learning, faculty changed their courses to better support students in the unique environment. A survey instrument was created to determine student responses to the course changes. As grades have been used in education research as a comparative bases for survey results in the past (Jones et al., 2010), this method is used herein. This research seeks to determine if grades were affected by the course changes and if students found these modifications helpful.

Methodology

Students from Northern Kentucky University in two different programs, were surveyed over their experience after the initial Covid-19 transition. The survey was distributed in Fall and Spring 2021. The students were enrolled in Construction Management (CMGT) and Engineering Technology (EGT) with survey distribution in the following courses: Introduction to Construction Management, Soils and Foundation Interaction, and Mechanical Systems for Construction, Industrial Electricity, Signals and Systems, and Mechatronic Systems. The CMGT courses were offered in a hybrid format which in this case consisted of a combination of synchronous, asynchronous, and in person. The EGT coursework delivery was split between two in person and one online. Students were asked to reflect on their experiences.

In order to create an environment for students to connect with each other and develop rapport with and within student groups (Harris et al. 2020), active learning techniques were employed in the classroom. Hybrid courses consisted of in person, synchronous, and asynchronous delivery modes to give the students a sense of togetherness while providing them with the flexibility they needed during COVID-19. Weekly updates have been sent every Monday to give a heads up to students about upcoming topics and deadlines. A “Jeopardy” style game was incorporated into all courses, which can be used online or in person. It has the same setting as Jeopardy Show which is a review of study materials for the exams while students competing to answer questions to gain extra credit. Zoom breakout rooms were used for all online group activities like case study, assignment, and project.

For the Soils and Foundation course, a group project required students to find a jobsite and apply outcomes from foundation design, stormwater pollution prevention plans, compaction, dewatering, and stabilization. Soils and Foundations labs included the Atterberg limit tests and hydrometer analysis which were conducted in person. The Mechanical Systems for Construction course included a group project where students had to illustrate course objectives in their own home or office including the type of HVAC system and sustainable strategies. There was a split between in person and online labs such as estimating pipes and fittings, sustainability case study, and isometric symbols and drawings. For the Introduction to Construction Management course, students worked as a group on case studies in Zoom breakout rooms, used an online simulation platform to learn and practice soft skills on the jobsite, and completed a group project to visit a jobsite through the semester and report its progress.

Group lab experiments incorporated into EGT161 and EGT404. The instructor had one-on-one (1:1) meetings with his EGT 161 students to discuss their progress, issues, problems, concerns, etc. since it was an introductory level course, and the research shows that freshmen were suffering the most from online delivery. EGT408 included Group lab experiments, assignments in form of Canvas Discussion Board, and Group Final Project. While the faculty introduced changes in the EGT courses and collected responses to the survey, that data is not discussed at length here as this paper is focused on Construction Management courses.

Student were asked to rate the following, using a 11- point Likert scale of 0 to 10, with 0 being not at all helpful and 10 being extremely helpful which has closest distribution to normal compared to 5-point and 7-point scales (Leung, 2017).

1. How in-person labs/lectures embedded in online course helped you to feel more connected to the university and your peers compared to completely online course?
2. How active learning elements such as jeopardy game, Zoom breakout rooms activities, and online software added to online course improved your online experience compared to completely online course?
3. How group projects/assignments included in online course helped you to feel more connected to your peers?
4. How sending weekly updates helped you to keep on track and layout the week?
5. How combination of synchronous (Zoom/live) and asynchronous (pre-recorded) lectures gave you flexibility to study at your own pace while still experiencing some degree of connectedness to the university compared to fully synchronous or asynchronous course?
6. How integrating self-discipline training or courses into curriculum especially for new college students will be a game changer during these unprecedented times?
7. Are you a female or international students? If yes, what accommodations you think you need/needed to better cope with COVID-19 situation compared to other students?

Results were determined by analyzing the data received from 111 students, based on survey responses on the perceptions of CMGT and EGT students about strategies incorporated into the courses. Although larger group was surveyed, this paper focuses on the construction management responses. One hundred and eighty nine CMGT students were enrolled in CMGT 101, 228, and 305 during Spring 2020, Spring 2021, and Fall 2021.Therefore, the average of final grades of CMGT courses when pandemic started were compared to the following semesters' when instructors applied more active and interactive learning activities to the classes. Both t-test and one way ANOVA tests were performed to ascertain if the grades significantly changed. Then, a more in-depth analysis was performed to lab, project, and exam grades to see if they changed.

Data Analysis

In this section, Excel software was used to analyze and interpret the data. Descriptive statistical techniques were used including identifying the mean, variance, coefficient of variation and one-way ANOVA (analysis of variance). Inferential statistical methods like the t-test were used when appropriate.

1- Survey Summary

After a fast transition to online delivery format in Spring 2020, modifications were made to online and hybrid courses in the following semesters. Active and interactive learning strategies were incorporated into the courses during the pandemic to make them more engaging for the students. Students were asked to submit a survey to measure how these strategies helped them to feel more connected to their peers and university and improve their online learning experience.

The average score to question one was 7.83 with a variance of 5.77 and coefficient of variation (CV) of 0.74. A CV equal or greater than 1 indicates a relatively high variation which is not the case here. It shows that students found in-person labs/lectures somewhat helpful. However, based on the policy at Northern Kentucky University, it was not mandatory to attend in-person labs or lectures. Therefore, it would affect the results since a small group of students took advantage of this opportunity while a majority of students who submitted the survey did not attend the in-person sessions.

The mean for the second question was 7.42. It shows that students believed that the "Jeopardy" game, Zoom breakout rooms, and online software improved their online experience to some degree. However, the variance is 6.68 and CV is 0.9 which is close to 1. A CV which equals 0.9 shows that the data points are spread out from the mean, and from one another. So, the variance can be interpreted as students had different perceptions about it as it was mentioned several times by the students in their final evaluation of the course that how much aforementioned activities helped them during COVID-19 to feel more connected.

The average score to question 3 was 7.1. This result indicates that the group projects and assignments were not perceived to help students feel more connected to their peers. However, the variance is 6.9 and CV is 0.97 which shows that some students may find it more helpful than others. The mean score for question 4 was 8.81. The variance of 3.64 and CV of 0.41 reveals that students strongly believed that the weekly update with alerts about upcoming topics and deadlines helped students to keep on track and layout the week ahead.

The average score to question 5 was 7.65, indicating that the combination of synchronous and asynchronous lectures gave the students the opportunity to study at their own pace while still experiencing some degree of connectedness to the university and their peers. The variance of 7.07 and CV of 0.93 for this question which indicates some students found it more helpful compared to the others. The mean for question 6 was 7.59 with a variance of 5.9 and CV of 0.78, which reveals that students feel that incorporating self-discipline training or courses into curriculum especially for new college students will dramatically affect their learning experience. A moderately high variance can come from the fact the survey was not submitted by only freshmen students, but also by sophomore, junior, and senior students who may have different perspectives and online experiences. The summary of results is shown in Table 1 to compare the answers for questions 1 through 6.

Table 1

Survey Summary

Question	Average	Variance	Coefficient of Variance (CV)
1-In person labs/lectures	7.83	5.77	0.74
2-Active learning elements	7.42	6.68	0.9
3-Group projects/assignments	7.1	6.9	0.97
4-Sending weekly updates	8.81	3.64	0.41
5-Combination of synchronous and synchronous	7.65	7.07	0.93
6-Self-desipline training/course	7.59	5.9	0.78

At the end of survey, students were given an open-ended question about what accommodations they need to better cope with the pandemic if they are female or international students. Some of them stated they are not sure about it, some wanted more in-person learning, and some showed interest in learning to manage the online classes and self-discipline. The latter refers to the fifth question and confirms that integrating self-discipline training or course into curriculum can better prepare students not only for unprecedented situation, but also equip them with a necessary skill throughout their life.

2- Grades Comparisons and Statistical Tests

COVID-19 hit the universities across the U.S. in Spring 2020 while there was many faculty with minimum experience with online learning and many universities were suffering from lack of adequate infrastructure for online learning. Therefore, a survey was distributed in Spring and Fall 2021 when faculty applied the lessons learned during the first phase of the pandemic in their courses, and the university established necessary infrastructure for online learning. In this section, a comparison is performed between the average scores of students in Spring 2020 to those in Spring and Fall 2021 to see if there were any improvements.

The CMGT 101 Introduction to Construction Management is an introductory level course and is the first Construction Management course that students take after being admitted to the CMGT program. Figure.1 illustrates how the average grades improved from spring 2020 (71.29) when pandemic hit U.S. to Spring 2021 (77.38) when the instructors adopted to pandemic and embedded more interactive and active practices into the courses. There was a slight decrease from Spring 2021 to Fall 2021 (75.58) which can be impacted by multiple factors such as having another cohort of students who were experiencing online learning in high school before entering the university environment. Some research shows that first-year and second-year student perceptions found online learning as the worst outcome of the pandemic compared to social distancing and unemployment (Karimi et al. 2021). This result shows that aforementioned strategies were helpful to improve freshmen performance.

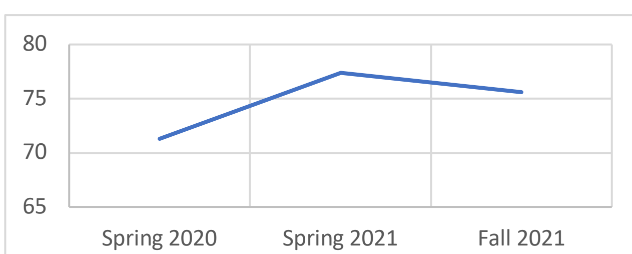

Figure 1. Average grades for CMGT 101

Furthermore, to determine if these changes were significant or not, a one-way ANOVA (analysis of variance) is used to compare the means of two or more independent groups to determine if their means are significantly different or not. Therefore, the test was run in Excel to examine the hypothesis that the average of grades in Spring 2020, Spring 2021, and Fall 2021 were significantly different. As shown in Table 2, p-value is 0.586 which is greater than 0.05. Since the alpha level was 0.05 for the test, the null hypothesis is accepted which states there is no significant difference between the means of groups.

Table 2

CGMT 101 One way ANOVA test

Source of variation	SS	df	MS	F	P-value	F crit
Between groups	206.019	2	103.0098	0.537	0.586	3.131
Within groups	13021.802	68	191.497			
Total	13227.822	70				

The CMGT 228 Soil and Foundation Interaction is a course including labs and a group project. Figure 2 shows that there was a slight decrease in the average of grades from Spring 2020 (81.24) to Spring 2021 (78.06), and it bounced back to 81.61 in Fall 2021. It can be interpreted that there are no significant differences among grades.

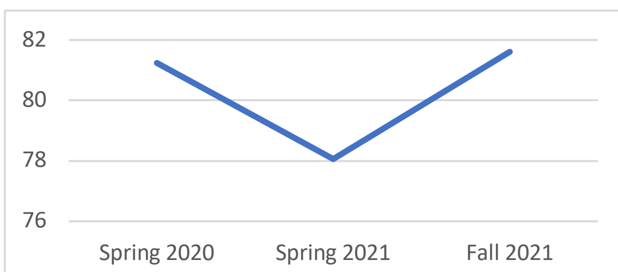

Figure 2. Average grades for CMGT 228

A one-way ANOVA test was run to have a scientific answer. The test proves there is no significant differences among average grades since p-value is greater than 0.05 which depicts that the null hypothesis is correct (Table 3).

Table 3

CGMT 228 One way ANOVA test

Source of variation	SS	df	MS	F	P-value	F crit
Between groups	57.73	2	28.86	0.537	0.893	3.182
Within groups	12814.228	50	256.28			
Total	12871.962	52				

The CMGT 305 Mechanical Systems for Construction is a course in which multiple labs and a final project are embedded. The average grades comparison indicates that the students' performance slightly changed from Spring 2020 (80.58) to Spring 2021 (79.08). However, it dropped to 74.1 in Fall 2021 (Figure 3). This course was offered in a hybrid mode in Spring and Fall 2021, and the in-person lab attendance was not mandatory according to Northern Kentucky University policy. Although some simulation software was used to facilitate conducting labs, but not all the labs could be performed using these software. This may have affected the grades of students who did not participate in all of the in-person labs.

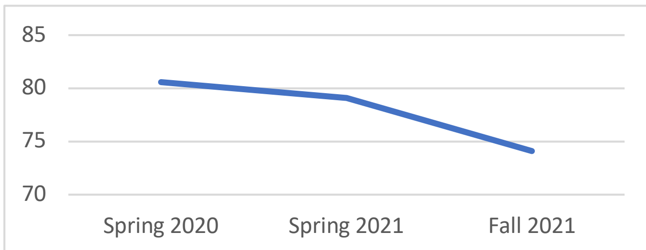

Figure 3. Average grades for CMGT 305

A one-way ANOVA test was conducted to see if the means of grades are significantly different. As it is shown in Table 4, p-value is 0.036 which is less than 0.05. The null hypothesis must be rejected, with the conclusion that the means are significantly different.

Table 4

CMGT 305 One way ANOVA test

Source of variation	SS	df	MS	F	P-value	F crit
Between groups	547.263	2	273.63	3.496	0.036	3.145
Within groups	4851.636	62	78.252			
Total	5398.899	64				

A T-test is a statistical test used to compare the means of two groups and tests the hypothesis to determine if a treatment has any effects on the population of interest (Bevans 2022). The T-test was conducted, and the result indicates that the average grades are significantly different between Spring 2020 and Fall 2021 since p-value is 0.001 which is less than 0.05 (Table 5).

Table 5

CMGT 305 T-test: two sample

	Spring 2020	Fall 2021
Mean	80.58	74.101
Variance	52.34	37.13
P(T<=t)two-tail	0.001	

3- Comparisons of Grade Details

After a close look at different grades, the results led to the following conclusions. The only improvement among all different sections of CMGT 101 was the project grades. The data depicts that the average grades of project improved dramatically from Spring 2020 (60.29) to Spring 2021 (85.31), and from Spring 2021 (85.31) to Fall 2021 (90.34) semesters. In CMGT 228, the project grades were improved from Spring 2021 (78.32) to Fall 2021 (80.23). Similarly, the final grades were improved from Spring 2021 (74.72) to Fall 2021 (78.94). Furthermore, overall quiz grades increased from Spring 2020 (80.56) to Spring 2021(81.61). More improvements were found in CMGT 305 which is a lab and project-based course. The project grades improved significantly from Spring 2021(73.0) to Fall 2021(91.09) . The midterm grades increased from Spring 2020 (79.48) to Spring 2021 (87.83). The quiz grades improved from Spring 2021 (74.17) to Fall 2021 (82.0).The lab and assignment grades improved from Spring 2021 (77.36) to Fall 2021 (89.62).

Conclusion and Recommendations

The data and analysis presented in this study show that incorporating active and interactive learning strategies into online and hybrid courses can improve online learning experience. Among aforementioned strategies, students reported greatest appreciation for the weekly updates for planning. In person labs and lectures were appreciated next in term of helping students feel more connected to the university and their peers. Students next recognized the combination of synchronous and asynchronous delivery modes helpful to experience connectedness to the university while having more flexibility.

Additionally, the results show the projects that were assigned for team-based collaborative learning opportunities, Zoom breakout rooms, and the “Jeopardy” game have improved the students’ online learning experience. Students emphasized in their formal evaluation at the end of the semester how Zoom breakout rooms created opportunities for them to develop rapport. They also found games in class, like “Jeopardy” helpful not only for active learning opportunities, but also for allowing students to interact.

Data analysis shows an improvement in CMGT 101, average course grades and project grades over the time. The results can be interpreted as following incorporating active and interactive learning elements into an introductory level course could help the students. These active and interactive learning elements allowed students to connect, collaborate, and submit the final project successfully which resulted in better final grades. By analyzing the data for CMGT 228, improvements were identified in the final exam, quiz, and project grades.

Although in the CMGT 305, the average grades decreased from Spring 2020 to Fall and Spring 2021, many improvements can be seen in the detailed grades. A significant improvement was found in the project, quiz, midterm exam, labs and assignment grades as well. The CMGT 305 course is lab based and relies on multiple labs and a final project. The data depicts that the aforementioned strategies enhanced online learning experience of the students specially for those courses which contain more teamwork and group activities. Making the conclusion based on solely the average grades is not possible since the university policy regarding to grading was an exception during Spring 2020 semester when COVID-19 hit the university.

The necessary infrastructure is in place for online learning, and more universities are offering online courses for Construction Management and Engineering major students these days. Although we cannot predict the future, we know that it is not the last pandemic we will face. Therefore, we need to proactively embed more active and interactive learning practices into online and in person courses. Moreover, it is necessary to include some in person activities in predominantly online courses in order to create a sense of belonging and togetherness which improves the performance of the students. Finally, integrating self-discipline training or courses into curriculum can better prepare students for unprecedented situation and life challenges.

References

Bevans, R. (2022).”An Introduction to T-Tests, Definitions, Formula and Examples.” Scribber. https://www.scribbr.com/statistics/t-test/

Harris, B.N., McCarthy, P.C., Wright, A.M., Schutz, H., Boersma, K.S., Shepherd, S.L., Manning, L.A., Malisch, J.L., and Ellington, R.M. (2020). “From panic to pedagogy: Using online active learning to promote inclusive instruction in ecology and evolutionary biology courses and beyond.” Ecology and Evolution. V.10: pp.12581–12612. https://doi.org/10.1002/ece3.6915

Jones, B. D., Paretti, M. C., Hein, S. F., & Knott, T. W. (2010). “An Analysis of Motivation Constructs with First-Year Engineering Students: Relationships Among Expectancies, Values, Achievement and Career Plans.” Journal of Engineering Education. V.99. N.4. pg. 319-336.

Karimi, B., Yazdanpour, M., Lewis, P. (2021). “COVID-19 Effects on Higher Education: A Case Study.” Paper presented at 2021 ASEE Annual Conference & Exposition Virtual Meeting, July 2021.

Lee, S.J., Ngampornchai, A., Trail-Constant, T., Abril, A., Srinivasan, S. (2016). “Does a case-based online group project increase students’ satisfaction with interaction in online courses?” Active Learning in Higher Education. V.17. N.3. pp. 249 –260. DOI: 10.1177/1469787416654800

Leung, S.O. (2011). “A comparison of psychometric properties and normality in 4-, 5-, 6-, and 11-point Likert scales,” Journal of Social Service Research, vol. 37, no. 4, pp. 412-421.

Liszka, J. (2013). “Charles Peirce’s Rhetoric and the Pedagogy of Active Learning, Educational Philosophy and Theory.” V.45 N.7. pp. 781-788, DOI: 10.1111/j.1469-5812.2011.00763.x

Mosier, R., Ramming, C. S., Adhikari, S., Agnew, R. J. (2022). “Student Post-Pandemic Perceptions of Supplemental Instructional Videos.” Paper presented at 2022 ASEE Annual Conference & Exposition, June 2022.

Shen, D., Cho, M.H., Tsai, C.L., Marra, R. (2013). “Unpacking online learning experiences: Online learning self-efficacy and learning satisfaction.” The Internet and Higher Education. V.19. pp. 10-17. https://doi.org/10.1016/j.iheduc.2013.04.001.

Stoytcheva, M. (2018). “Students’ Perceptions of Online Collaboration in a Distance Learning French Language Course.” AIP Conference Proceedings. V.2048. https://doi.org/10.1063/1.5082048

Stump, G.S., Hilpert, J.C., Husman, J., Chung, W.C., Kim, W. (2011). “Collaborative Learning in Engineering Students: Gender and Achievement.” Journal of engineering education (Washington, D.C.) 100.3 pg.475–497.

Investigating the Barriers to Construction Automation from the Industry's Perspective

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Industrialization of construction projects has been shown as an effective tool to make them more predictable, sustainable, and productive. In the past four decades, studies have demonstrated automation as an effective tool for increasing productivity, precision, and safety in construction projects. Despite these benefits, industry professionals seem to be skeptical or unwilling to effectively adopt many automation methods in their projects. The steppingstone in bridging this gap is identifying the existing barriers from the lens of the industry. In this research, construction industry professionals were interviewed through a survey to identify the challenges they face to utilize new automated technologies. The results showed thirteen major barriers that are discussed. Using the relative importance index method, the barriers are then ranked based on their criticality. According to the findings, the concerns and demands of the industry in each category and possible approaches to meet them were also examined. The paper is expected to create insights into how construction automation can be evolved to more practically and positively influence the construction industry by meeting the concerns of the end-users of the automated techniques.

Key Words: Construction, Automation, sustainability, human laborers

Introduction

One of the most revolutionary changes in the building industry has been the introduction of automation and robotics (Bock and Linner, 2015). The practical application of automated technologies is, however, still in its infancy, and low economic interest is seen as the primary barrier (Mahbub, 2008). Lack of performance and inefficient management practices create roadblocks to sustainability that can only be overcome with cutting-edge tools (Goodier and Pan, 2010). Additionally, construction automation is seen as a practical solution to enhance sustainability performance in a variety of ways, including the reduction of construction waste, the conservation of natural resources, the enhancement of workplace safety, and the provision of a high-quality living environment (Bock and Linner, 2012; Castro-Lacouture, 2009).

A fundamental shift from constructing buildings to producing them is on the horizon. Applying construction automation is widely recognized as an effective approach that is expected to continue revolutionizing construction methods. Additionally, recent calls for environmental responsibility as well as increased safety on construction fields serve as a trigger for the large-scale use of automation. Conversely, many automation practices and methods are still far from being broadly practiced by the industry (Kamaruddin et al., 2016). The slow adoption of construction automation contrasts with the pulling factors such as high price and low availability of human labor in the construction industry and the need for improving precision throughout the design and construction processes (Akomah et al., 2020). Limited research has been conducted to investigate the barriers to the application of automation in design and construction. For a more effective approach to identifying these barriers, the concerns of industry professionals to improve the practicality of the new technologies should be examined. This study attempts to fill this gap by investigating the factors that discourage construction professionals from utilizing construction automation methods.

Background

Despite various attempts to define construction automation, there seems to be a persisting disagreement in the way it is defined. This is detrimental to reaching a unanimous understanding of construction automation and its mission (Bock and Linner, 2015; Chen et al., 2018). According to Richard (2005), five levels of industrialization can be assumed. These include prefabrication, mechanization, automation, robotics, and reproduction (Figure 1). Prefabrication is more concerned with the location of production, whereas the next three levels (Mechanization, automation, and robotics) seek to replace human labor with machines (Richard, 2005).

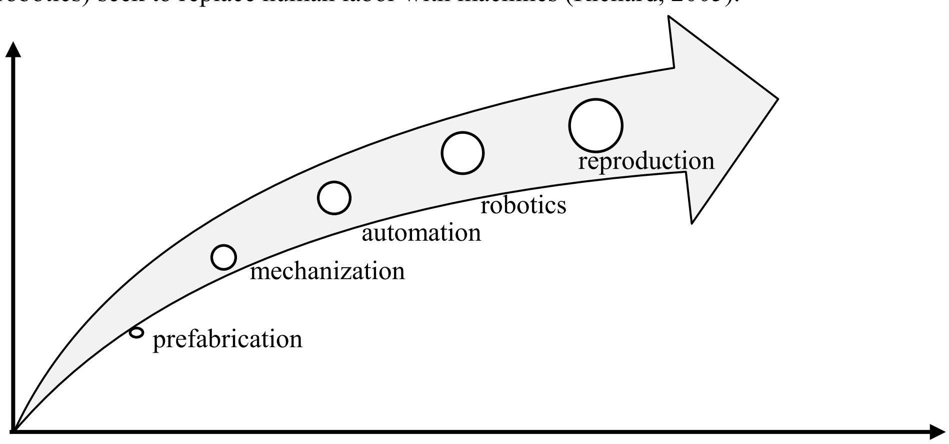

Figure 2. Five levels of industrialization

Although there exists a plethora of research on construction automation, the industry appears to fall significantly behind in adopting the products of research (Pan et al., 2020). This can indicate a gap between the technologies the industry can practically apply and researchers' perspectives on how the technology used in the industry could be improved. Additionally, the definition and applications of automation in the construction industry have evolved and expanded significantly in the last decades. Automation applications could range from communication, and image processing focused on monitoring, to remotely controlled and autonomous robots. Effective categorization, plausible explanations, universal definitions, and an easily comprehensible explanation of applications for each category could potentially facilitate the adoption of these technologies.

Methodology

This study attempts to find the challenges the construction industry needs to overcome to adopt construction automation technologies in projects. It should be noted that construction automation can include various stages of prefabrication, on-site construction, operation, maintenance, demolition, and recycling. In this paper, automated technologies are the ones used in different stages of physical on-site construction. On-site robotic automation has not yet played a significant role in the construction industry (Melenbrink et al., 2020). Other widespread technologies such as building information modeling, or using software tools for planning, scheduling, and estimating projects are out of the scope of this study. The steps taken to identify the following steps were taken.

Selecting the Sample for the Interview

For the interview, a sample of 33 construction contractors were randomly selected. The minimum years of experience for each contractor was 17 and the average was 26 years. 14% of the contractors were primarily involved in heavy construction projects, 55% in residential projects, and the remaining 31% in commercial projects. The contractors were selected from reputable companies with a long background in the industry that commonly can afford to adopt new and costly technologies. Most (68%) of the contractors had been involved in projects as managers. The majority of the interviewers (78%) had experience in delivering projects in different states and regions of the United States of America.

Step 1. Investigating the Potential Barriers to the Literature

Research and development in the fields of automation were reviewed and then a critical interpretive synthesis was carried out to develop the conceptual framework. Books and research papers published in reputable journals of both fields were investigated, and international standards for sustainable building design and construction were also examined.

Step 2. Conducting a Survey for Critical Ranking of the Barriers

A survey was developed to rank the barriers. Using an online questionnaire and hard copies the survey was distributed. Respondents were asked to rate each potential barrier with a number between ‘1’and ‘5’, where ‘1’ indicated the lowest and ‘5’ indicated the highest level of criticality.

Step 3. Analyzing the Data and Interpreting the Results

The results of the survey were analyzed using the Relative Importance Index (RII) method. RII is a method that aids in finding the contribution a particular variable makes to the prediction of a criterion variable both by itself and in combination with other predictor variables (Tafazzoli and Shrestha, 2017, Tafazzoli, Tafazzoli, et al., 2020). Equation 1 was used.

$$RII=\frac{\Sigma W}{A\ X\ N} \qquad (0\leq RII\leq 1) \qquad (1)$$

where:

W = the weight given to each factor by respondents and ranges between 1 and 5
A = the highest weight (i.e., 5 in this case)
N = the total number of respondents

Results

The barriers to maximizing the application of automation in construction were investigated by reflecting on the findings of similar research and combining them with the outputs of the survey. The barriers in the viewpoint of the developers were categorized into 13 factors. Table 1 shows the results.

Table 1

Barriers to construction Automation from the Industry's Perspective

Barriers	Description
B1	Disparity and lacking consensus in the application of automation in construction
B2	Fear of elimination of jobs when human laborers are replaced with automated technologies
B3	Challenges in maintaining or updating the technologies
B4	Uncertainties about the advantages of utilizing automation and the return rate of additional costs
B5	Higher initial costs of purchasing, installing, etc. when compared with human laborers
B6	Fragmented nature of the construction industry and the uniqueness of each project
B7	Resistance to change inherited in the construction industry
B8	Challenges of finding the right people to operate the new technologies
B9	Incompatibility of the technologies with existing practices and current construction operations
B10	Time constraints and additional mobilization time needed for procuring automated technologies
B11	Lack of guidance and training about the existing opportunities for utilizing automation
B12	Transferability and flexibility of automated methods to different projects
B13	Accessibility to the new automated technologies (regardless of their price)

Using the relative importance index method, the criticality for each of the barriers was computed. The corresponding RII value, therefore, represents the significance of the barrier. The results shed light on the major concerns of industry professionals about adopting new technologies more actively in their projects. Figure 2 shows the results.

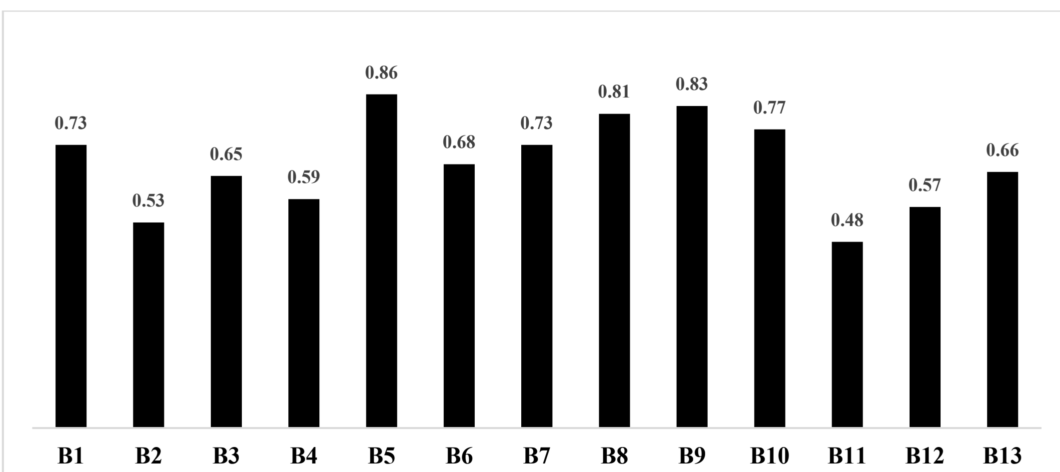

Figure 2. Relative importance index of the 13 barriers from the statistical analysis

Discussion

Disparity and lacking consensus in the application of automation in construction. The complexity, uniqueness, and inherent riskiness of modern construction projects require traditional practices, which rely heavily on trial and error, to evolve and improve. Additionally, the shortage of the workforce and the growing attention to occupational safety and the health of the employees explains why a paradigm shift to more automated practices in construction is crucial. Although many practices and methods have been introduced, the sector is still immature, and the actual implementation of automation and robotics in the workplace is restricted and behind the curve compared to other industries.

Fear of elimination of jobs when human laborers are replaced with automated technologies. From the industry's standpoint, resistance to replacing humans is obvious. The historical assumption about using robots and automated machines is that they are a threat to employment due to reducing or eliminating the human workforce. The findings of the research in many cases support this assumption (Acemoglu and Restrepo 2020; Frey and Osborne 2017). The interview, however, shows that contractors seem to underestimate the new jobs construction automation can create. The production of these technologies, as well as transport and maintenance, can create new employment opportunities. In the meantime, it should be noted that the types of jobs that are created due to automation, could vary significantly from the jobs that are eliminated because of it. The majority of the interviewed contractors mentioned that the concerns of the laborers must be closely addressed to increase the chance of shifting to new technologies. Similar findings can be found in the literature showing that transforming construction into production is a source of concern, particularly among low-skilled workers (Pan et al., 2018).

Challenges in maintaining or updating the technologies. In addition to the initial casts, automation requires training, transport of heavy equipment, and maintenance that add to the operational costs. It can be inferred from the survey's comments that a fundamental approach to boosting automation is modifying these technologies with a focus on decreasing the challenges of their application and maintenance. The construction sector is thought to be price sensitive to technological utilization (Mahbub, 2012). Participants discussed the costs of not just purchasing but also maintaining and updating new technologies that can discourage them from adapting these technologies. Considering the rapid evolution and changes in the existing technologies, keeping up with these changes would be an additional concern for a project utilizing these automation tools

Uncertainties about the advantages of utilizing automation and the return rate of additional costs. Construction projects inherently deal with plenty of risks and concerns throughout the process and are less likely to be tolerant or willing to accept additional challenges when they are skeptical about the potential benefits of modifying their traditional methods. Measuring the precise cost benefits of construction automation is challenging for a variety of reasons. Firstly, the costs and potential savings could be significantly different if they are measured in the long-term or short-term. Additionally, some savings might not be easily measured. For instance, increased safety and productivity resulting from automation cannot easily be evaluated by monetary values.

Higher initial costs of purchasing, installing, etc. when compared with human laborers. These findings are in agreement with the existing literature. There is a myriad of research showing the substantial initial costs of construction automation as a barrier to its widespread application (Chen et al., 2018; Kamaruddin & Mahbub, 2008). In the meantime, there is research showing the cost-effectiveness of replacing automation with human labor forces (Pan et al., 2018). A compelling argument for why automation can still be cost-effective is its capability in reducing the significant indirect costs of labor including insurance, training, retirement, and overtime pay to name a few.

Fragmented nature of the construction industry and the uniqueness of each project. Construction is a dynamic and intricate process. The fragmentation and uniqueness of projects makes it difficult to design and develop practices and methods that could be used universally. This particularly applies to higher levels of industrialization such as robotics and reproduction. Additionally, the disparity in the construction projects' nature creates an additional challenge in developing guidelines and consensus on the application of automation in construction. This barrier was independently discussed in B1. Not only do developed and developing countries have different approaches to project management, but inconsistency also exists among developing countries themselves (Raheem et al., 2011). This is because different countries have various criteria for what constitutes an acceptable level of performance.

Resistance to change inherited in the construction industry. The construction industry is notorious for adopting new technologies and methods. Cognitive, emotional, and behavioral resistance to change have been identified as distinct aspects of the phenomenon in the literature (Lines 2015; Erwin and Garman, 2010). The cognitive dimension entails workers' thoughts about the change, such as whether or not they believe they have the skills necessary to be successful in their new roles (Giangreco & Peccei, 2005). The affective dimension refers to workers' subjective emotional and mental responses to the transition (Denhardt et al., 2009). Unlike the first two dimensions, which are generally understood to be the causes of resistance, the behavioral dimension investigates resistance in terms of employees' action responses (Fiedler, 2010; Giangreco and Peccei, 2005). Because it is the only directly observable dimension, behavioral resistance to change is the sole focus of this investigation.

Challenges of finding the right personnel to operate the new technologies. Human labor is crucial in the construction industry, despite employing a disproportionately large number of low-skilled workers. Due to the current worldwide expansion of the construction industry (Ceric, et al., 2020, Al-Bayati et al., 2020), a severe shortage of qualified workers has emerged as a worldwide problem. Therefore, poor project performance and increased costs result from a lack of skilled workers (Karimi, et al., 2018). Moreover, it can have an adverse effect on the timely completion of construction projects and the delivery of projects (Aiyetan & Dillip, 2018). A study conducted in 2017 in the United States reveals that there are severe shortages of a variety of skilled construction workers in developed construction industries like that of the United States (Azeez et al., 2019). Further evidence of a shortage of skilled workers in Texas, USA, was presented in a separate study (Bigelow, et al., 2019), which also highlighted the primary incentives for keeping people employed in the construction industry. The shortage of the workforce becomes a more severe problem when it comes to a skilled workforce. Considering the relatively short history of emerging technologies finding reliable personnel who can operate these technologies serves as a concern in the wide adoption of construction automation.

Incompatibility of the technologies with existing practices and current construction operations. To orchestrate a construction project, numerous components related to labor, material, and equipment must work hand in hand with minimal errors. The homogeneity of the workforce in traditional construction can facilitate communications and team effort. In a partially automated project, however, such flexibility might be negatively affected as verbal communication between different sections during the construction on the field varies from traditional mouth-to-mouth communications. On the other hand, it should be noted that communication issues persist to be a major challenge even in traditional construction projects that rely on human laborers. For instance, mismanaging cultural diversity has significant consequences, including a decrease in morale, productivity, quality issues, and accident rates (Loosemore et al., 2022). The involvement of personnel from various cultures in a project can potentially create communication challenges because when recipients interpret a message through their own cultural lens, which may be very different from the intended meaning of the sender, misunderstandings may occur. Such misinterpretation rises as the distance between the two cultures widens (Loosemore et al., 2022). New communication tools, which are commonly connected to automated technologies can respond to miscommunication issues caused by individuals' cultural lenses. This is acquired through universal digital communication languages, codes, and symbols that mean the same to all recipients.

Time constraints and additional mobilization time needed for procuring automated technologies. When evaluating a project, both the owner and the contractor place a premium on how quickly it can be completed. Often, the most troublesome construction disputes involve delays and failure to complete the work promptly. Delays may originate from any number of sources, including but not limited to the parties to a contract or any other third parties. Every essential component of the project that involves uncertainty can increase the risk of delays. A common remedy to mitigate the risk of delays is to minimize unfamiliar situations. Considering the relatively short history of many construction automation tools, there seems to be a precaution in the industry about utilizing them. The additional time for mobilizing automated technologies could also be linked to their availability or finding the staff that can operate them. In some cases, additional training would also be needed. This explains why compared to traditional recruiting and procurement methods for human laborers, mobilizing and installation of automated technologies could be significantly more time-consuming.

Lack of guidance and training about the existing opportunities for utilizing automation. The research in construction automation has extensively demonstrated its potential benefits. However, the willingness in the industry to adopt the new technologies falls significantly behind. The interview revealed that one reason for this gap is the lack of a systematic approach that could facilitate faster adoption of emerging technologies. The interviewees believed that the use of automation is still more limited to information and communication. For instance, building information modeling, or online software tools that enable the team to communicate in real time are now widely accepted in the industry. Whereas the application of other high-tech tools such as drones is still very limited. The two parameters that the interviewees were skeptical about were the reliability and accessibility of these technologies. When these technologies play a pivotal role in the project, the team needs to rely on a responsive support system that is available in a timely manner in case of a breakdown.

Transferability and flexibility of automated methods to different projects. Unlike other industries, the additional initial costs of the project's automation, cannot necessarily be fully transferred to the production of the next project. This could be associated with the uniqueness of each project, including the type of construction, the project layout, as well as quantities, and dimensions, to name a few. This indicates the necessity of making these technologies more flexible and transferable to enable them to be used in different settings. There is little doubt that methods of automation that aim for a broad impact on the industry will ultimately be judged based on the level of obtained organizational flexibility (Wagner et al., 2020).

Accessibility to the new automated technologies (regardless of their price). Accessibility to new technologies not only varies in different countries but also in different regions of the same country. This is highly dependent on the type of automated technologies. More advanced robotics are available only on a limited scale. It is imperative that without reliable access to such technologies widespread application of them remains a farfetched goal.

Summary and Conclusion

The construction industry's major challenges such as low quality and productivity, labor shortages, occupational safety, and hazardous working conditions have prompted a drive for further industrialization, construction automation, and robotics application on building sites. The evolution of construction and automation and the significant contribution of construction automation to the triple bottom lines of sustainability create a massive potential for their integration to maximize the sustainability benefits of automation. Such an approach requires investing in understanding the industry's concerns and limitations to form the automated technologies in such a way that they could be more smoothly adopted on construction sites. In doing so, particular attention must be paid to forming a consensus about the applications of automation in construction. More accurate awareness and understanding of the available technologies and their applications are also needed. Another essential parameter that can be inferred from the results of the research, is the cost-effectiveness and ease of use of the new technologies. To overcome the inherited resistance to change in the industry, the new technologies should lead to savings for the contractors. This incentive seems to overweigh other potential benefits of automation from the viewpoints of contractors. The reliability and accessibility of automated technologies also play a significant role in accepting the risk of a shift from conventional approaches to high-tech methods.

Expanding the construction machinery manufacturing industry, developing capacity and capability, strengthening research, development, and commercialization, and educating the public about the benefits of mechanization and automation in construction are some of the recommendations to meet these challenges. Contractors paying less in construction levies, acquiring equipment under a leasing arrangement, receiving government financial aid and tax exemptions, and paying less in import duty and sales tax on heavy construction machinery are some of the other suggested methods to incentivize the industry to utilize automation. This process is expected to take time, but the more the industry demands, and concerns are understood and met, the faster this evolutionary process is expected to take place.

References

Al-Bayati, A. J., Tafazzoli, M., York, D. D., & Umar, T. (2020). Cyclical construction workforce shortage: an evaluation of the current shortage in Western North Carolina.

Acemoglu, D., & Restrepo, P. (2020). Robots and jobs: Evidence from US labor markets. Journal of Political Economy, 128(6), 2188-2244.

Aiyetan, O.A.; Dillip, D. (2018). System dynamics approach to mitigating skilled labour shortages in the construction industry: A south African context. Constr. Econ. Build. 18, 45–63.

Akomah, B. B., Ahinaquah, L. K., & Mustapha, Z. (2020). Skilled labour shortage in the building construction industry within the central region. Baltic Journal of Real Estate Economics and Construction Management, 8(1), 83-92.

Azeez, M., Gambatese, J., & Hernandez, S. (2019). What do construction workers really want? A study about representation, importance, and perception of US construction occupational rewards. Journal of Construction Engineering and Management, 145(7), 04019040.

Bamgbade, J.A.; Kamaruddeen, A.M.; Nawi, M.N.M. Malaysian construction firms’ social sustainability via organizational innovativeness and government support: The mediating role of market culture. J. Clean. Prod. 2017, 154, 114–124.

Bigelow, B. F., Zarate, V., Soto, J., Arenas, J., & Perrenoud, A. (2019). Attracting and retaining tradespeople, an evaluation of influencers on construction workers in two different trades in Texas. International Journal of Construction Education and Research, 15(3), 163-178.

Bock, T., & Linner, T. (2015). Robotic industrialization. Cambridge University Press.

Castro-Lacouture, D. (2009). Construction automation. In Springer handbook of automation (pp. 1063-1078). Springer, Berlin, Heidelberg.

Ceric, A., & Ivic, I. (2020). Construction labor and skill shortages in Croatia: causes and response strategies. Organization, Technology and Management in Construction: an International Journal, 12(1), 2232-2244.

Chen, Q., de Soto, B. G., & Adey, B. T. (2018). Construction automation: Research areas, industry concerns, and suggestions for advancement. Automation in Construction, 94, 22-38.

Erwin, D. G., & Garman, A. N. (2010). Resistance to organizational change: linking research and practice. Leadership & Organization Development Journal.

Escamilla, E. Z., Habert, G., & Wohlmuth, E. (2016). When CO2 counts: Sustainability assessment of industrialized bamboo as an alternative for social housing programs in the Philippines. Building and Environment, 103, 44-53.

Fiedler, S., (2010). Managing resistance in an organizational transformation: a case study from a mobile operator company. Int. J. Proj. Manag. 28, 370–383.

Frey, C. B., & Osborne, M. A. (2017). The future of employment: How susceptible are jobs to computerisation?. Technological forecasting and social change, 114, 254-280.

Goodier, C. I., & Pan, W. (2010). The future of UK housebuilding.

Kamaruddin, S. S., Mohammad, M. F., & Mahbub, R. (2016). Barriers and impact of mechanization and automation in construction to achieve better quality products. Procedia-Social and Behavioral Sciences, 222, 111-120.

Karimi, H.; Taylor, T.R.B.; Dadi, G.B.; Goodrum, P.M.; Srinivasan, C., (2018). Impact of skilled labor availability on construction project cost performance. J. Constr. Eng. Manag. 144, 04018057.

Karji, A., Namian, M., & Tafazzoli, M. (2020). Identifying the Key Barriers to Promote Sustainable Construction in the United States: A Principal Component Analysis. Sustainability, 12(12), 5088.

Lines, B. C., Sullivan, K. T., Smithwick, J. B., & Mischung, J. (2015). Overcoming resistance to change in engineering and construction: Change management factors for owner organizations. International Journal of Project Management, 33(5), 1170-1179.

Loosemore, M., & Lee, P. (2002). Communication problems with ethnic minorities in the construction industry. International Journal of Project Management, 20(7), 517-524.

Mahbub, R. (2008). An investigation into the barriers to the implementation of automation and robotics technologies in the construction industry (Doctoral dissertation, Queensland University of Technology).

Melenbrink, N., Werfel, J., & Menges, A. (2020). On-site autonomous construction robots: Towards unsupervised building. Automation in construction, 119, 103312.

Pan, M., Linner, T., Pan, W., Cheng, H. M., & Bock, T. (2020). Influencing factors of the future utilisation of construction robots for buildings: A Hong Kong perspective. Journal of Building Engineering, 30, 101220.

Pan, M., Linner, T., Pan, W., Cheng, H., & Bock, T. (2018). A framework of indicators for assessing construction automation and robotics in the sustainability context. Journal of Cleaner Production, 182, 82-95.

Ribeirinho, M.J.; Mischke, J.; Strube, G.; Sjödin, E.; Blanco, J.L.; Palter, R.; Biörck, J.; Rockhill, D.; Andersson, T. The Next Normal in Construction: How Disruption Is Reshaping the World's Largest Ecosystem; McKinsey & Company: Zurich, Switzerland, 2020.

Richard, R. B. (2005). Industrialised building systems: reproduction before automation and robotics. Automation in construction, 14(4), 442-451.

Tafazzoli, M., & Shrestha, P. (2017, October). Factor analysis of construction delays in the US construction industry. In International conference on sustainable infrastructure (pp. 111-122).

Tafazzoli, M., Kermanshachi, S., Shrestha, K., & Kisi, K. (2020, November). Investigating the relative importance barriers to sustainable construction related to owners, contractors, and government. In Construction Research Congress 2020: Infrastructure Systems and Sustainability (pp. 341-350). Reston, VA: American Society of Civil Engineers.

Vermeulen, B., Kesselhut, J., Pyka, A., & Saviotti, P. P. (2018). The impact of automation on employment: Just the usual structural change?. Sustainability, 10(5), 1661.

Wagner, H. J., Alvarez, M., Groenewolt, A., & Menges, A. (2020). Towards digital automation flexibility in large-scale timber construction: integrative robotic prefabrication and co-design of the BUGA Wood Pavilion. Construction Robotics, 4(3), 187-204.

Wolfgang, M. (2016). The Robotics Market—Figures and Forecasts. Ro-boBusi-ness, Boston Consulting Group: Boston, MA, USA.

Workers' Fatigue in Construction Projects, Assessment, Detection, and Mitigation, A Review

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Despite the increased focus on safety management in recent years, the construction industry's accident rate remains extraordinarily high. High physical demands and difficult work environments, which lead to physical and mental fatigue in construction workers, are one of the key causes of the continuous high rate of construction accidents. This study begins with a description of the causes and effects of fatigue among construction workers. In the second section, the subjective and objective evaluation methods for physical fatigue are discussed. The advantages and drawbacks of fatigue measurement technologies such as self-reporting and on-body sensors are reviewed. Thirdly, the major approaches for predicting and quantifying fatigue, as well as their limitations, are discussed. In addition, mitigation and management of fatigue in construction projects, as well as successful methods such as work-rest people scheduling, are discussed. The paper concludes by highlighting the fragmentation and inconsistencies in the available research as well as the opportunity for future studies to fill the existing gaps. The study is designed to give an effective evaluation of the available information on defining, assessing, detecting, quantifying, mitigating, and managing fatigues, as well as shed light on the recommended and required future steps in research for each category.

Key Words: Fatigue, Assessment, Detection, Prediction, Mitigation

Introduction

The construction industry had the greatest accident rate of any sector in the US economy in 2016 which equated to 19% of all industrial deaths (Hallowell & Hansen, 2016). Injuries in the construction sector are a leading cause of hospitalization, disability, and death. Over sixty thousand fatalities are reported annually from building projects around the world (Lingard, 2013). The cost of project accidents has a major influence on profit margins, negatively affects project success, and in certain cases poses a threat to the continued existence of construction enterprises (Zou & Sunindijo, 2015).

A great deal of effort has been put into the research to identify and comprehend the causes of construction incidents (Rajendran & Gambatese, 2009). Workers in the construction industry need to maintain a state of constant vigilance and attention to the ever-changing environment surrounding them at all times in order to identify potential dangers and avoid accidents and injuries. Because of the excessive amount of work, a worker has a greater risk of engaging in construction tasks when under the influence of fatigue (Xing et al., 2020).

Causes and Effects of Construction Workers' Fatigues

Construction workers are required to maintain a state of constant alertness and attention to the ever-changing environment surrounding them at all times in order to identify potential dangers and avoid accidents and injuries. Because of the excessive workload, a worker has a greater propensity to engage in construction activities while in a fatigued state, which results in a poor cognitive condition, including a slowed reaction time, reduced vigilance, reduced ability to make decisions, task distraction, and loss of situational awareness.

According to Lewis and Wessley (1992), a general definition of fatigue is "the lassitude or exhaustion of mental and physical power that occurs from muscular effort or mental activity. The consequence of sustained work, weariness, or exhaustion of physical or mental strength that might result in a temporary lack of ability to work are all examples of fatigue. Constantly, construction work necessitates lengthy shifts without proper breaks, as well as working in difficult climatic conditions and/or restricted areas. These conditions can raise the likelihood of physical fatigue. Table 1 shows the causes of construction fatigue in the literature.

Table 1

Effective factors in construction fatigue in the literature

Causes	Authors/ investigators
Climate (temperature and humidity)	• Al-Bouwarthan et al., 2019
Working at Heights	• Hsu et al., 2008; • Chang, 2009
Overtime shifts	• Fang et al., 2015
Sleep deprivation	• Powell & Copping, 2010
Mental exertion	• Xing et al., 2020
Muscular exertion	• Jebelli et al., 2020
Work environment factors (light, vibration, noise, etc.)	• Jiao et al. (2004)
Motivation factors (rewards, voluntary vs. compulsory tasks, etc.)	• Van der Hulst & Geurts, 2001 • Beckers et al., 2008
The social environment at the workplace	• Bültmann et al. (2001)

Construction fatigue could be categorized into physical, mental, and emotional fatigue. Physical fatigue, which is reduced physical functioning capacity, is the primary type of fatigue that the literature has focused on. The research in this field could be categorized into studying the causes and consequences, as well as detection and prevention techniques. Measuring mental and emotional fatigue requires more complex neurophysiological tools. Mental fatigue is a phenomenon that is experienced by people who have been involved in a protracted period of demanding mental effort which causes a feeling of being fatigued or inactive and leads to low job efficiency and even life-threatening behaviors (Xing et al., 2019).

It should be noted that mental factors could play a significant role in determining the level of fatigue in situations that have a common cause. For instance, when fatigue is driven by working overtime, different levels of fatigue could be observed based on the type of overtime work. For instance, mandatory, low reward, low autonomy, and highly demanding overtime work could lead to a higher level of fatigue when compared with voluntary overtime which is highly rewarded, and included less demanding tasks (Techera, 2017). Bültmann et al. (2001) found that relationships with coworkers, bosses, and subordinates play a significant impact in the development of mental fatigue. Additionally, environmental elements such as temperature, light intensity, vibration, and noise are all associated with increased levels of fatigue (Krause et al. 1997).

The Consequences of Construction Workers' Fatigue

According to the Bureau of Labor Statistics (2016), exhaustion and overexertion were the cause of 33 percent of all occupational accidents and illnesses that occurred on construction sites in the United States. Worker tiredness causes drowsiness, poor decision-making, slower reflexes, diminished mental and physical sharpness, and a less cooperative attitude (Techera, 2017). It has been demonstrated that the negative consequences of fatigue are exacerbated in construction workers by long working hours, work environments that are hot and humid, and excessive workloads (Anwer et al., 2021).

According to Spurgeon et al. (1997), there are primarily two reasons why fatigue poses a threat to laborers' safety. Firstly, workers' ability to detect and respond to new information is negatively impacted when they are fatigued (Reiner and Krupinski 2011). Second, fatigue makes it harder for a person to understand risk, so he or she subconsciously takes on more risk than he or she normally would when not tired (Tixier et al. 2014).

Some of the effects of worker fatigue cannot be precisely measured. For instance, fatigue lowers the quality of life and impairs the immune system of workers, which might in turn have a broad range of ripple effects. The construction industries, particularly those in developed nations or regions, should pay more attention to fatigue detection and prevention due to a number of workforce difficulties that may impede the sector's growth. Among these problems are rising labor wages, an aging workforce, and a shortage of labor (Yu et al., 2019).

Table 2

Consequences of construction fatigue in the literature

Consequences	Authors/ investigators
Musculoskeletal disorders (MSDs)	• Merlino et al., 2003
Work errors	• Aryal et al., 2017
Reduced Productivity and poor performance	• O'Neill & Panuwatwanich, 2013
Loss of motivation	• Hallowell, 2010; DeVries et al., 2003
Compromised Safety (job site accidents)	• Namian et al., 2021; Swaen et al., 2003
Cognitive degradation (attention, vigilance, responsiveness)	• Van Dongen & Dinges, 2005 • Tixier et al, 2014
Reduced client satisfaction	• Dall'Ora et al., 2016

Quantification of the outcomes of fatigue in construction projects is complicated as it is difficult to attribute the negative outcomes such as lost productivity only to fatigue. However, According to the National Safety Council (NSC, 2018), a typical company with 10,000 workers incurs a cost of more than $1 million per year as a result of fatigue. This cost is broken down as follows: $272,0 0 0 is due to absenteeism, and $776,0 0 0 is due to working while fatigued. In another study, Rosekind et al. (2010), found that reduced productivity due to fatigue costs companies between $1,293 and $3,156 per employee annually.

Assessment of Construction Workers' Fatigues

Considering the numerous consequences of fatigue in construction assessing the level of physical fatigue experienced by construction workers is an essential first step in reducing the likelihood that these workers may become physically fatigued. Despite its significance, fatigue is frequently only discovered after a serious accident (Reiner and Krupinski 2011).

Fatigue monitoring methods

There are two primary methods for evaluating fatigue: subjective and objective. The subjective evaluation of exhaustion is based on an individual's impression of the symptoms associated with fatigue. Among these symptoms are drowsiness, loss of energy, and physical limitations. The seeming inability to directly evaluate these subconstructs led to their subjective evaluations as the most accurate methods for measuring weariness. Recently, new technologies have enabled the direct assessment of specific physical factors, such as neuronal activity or cardiorespiratory parameters, that vary under the influence of weariness. These technologies have made objective measurements possible. . Figure 1 shows some fatigue assessment methods and their corresponding tools or technologies(Yu et al., 2019). Recent advancements in wearable sensing and computing have contributed to the development of novel methods for enhancing the health and safety of construction workers. However, there is no agreement on how fatigue should be quantified due to the complicated physiological nature of fatigue (Techera et al., 2018).

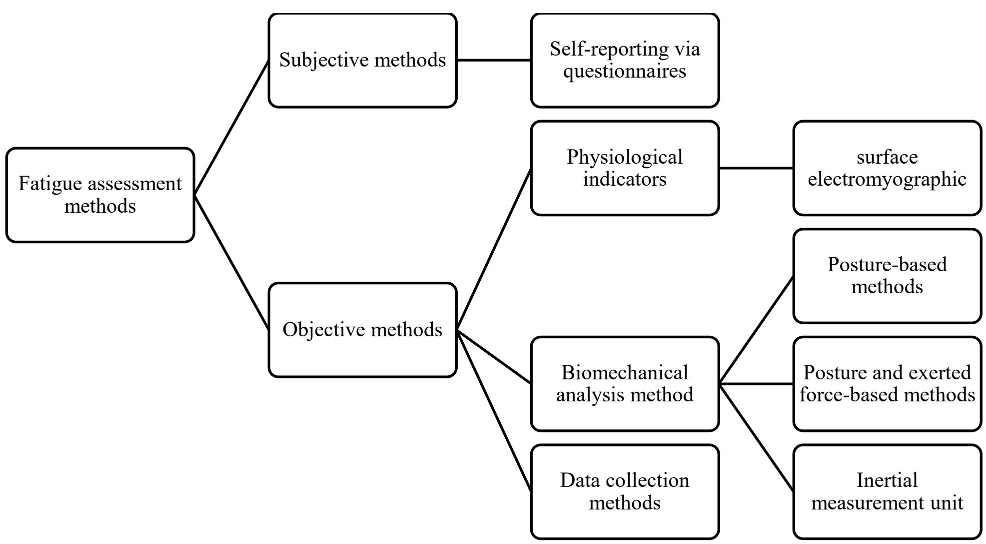

Figure 1. Fatigue assessment methods and their corresponding tools or technologies

Self-reporting via Subjective questionnaires. Subjective techniques rely on the workers' own self-reporting of how they feel in terms of their physical fatigue. Self-reporting has always been the foundation upon which fatigue monitoring in the construction industry is built. These approaches are inefficient for continuous fatigue monitoring since they call for the manual gathering of responses.

On-body sensors. Indicators of cardiovascular health include the heart rate, the temperature of the skin, and breathing rate, all of which often rise when the body is subjected to a significant amount of physical stress (Cheng et al., 2013; Gatti et al., 2014; Kirk & Sullman, 2001). The indicators are measured using sensors, which are often fastened closely to the worker's body to assure the accuracy of the readings but can be a nuisance for the workers while they go about their daily job routine. Examples of these assessment technologies are surface electromyography (sEMG) sensors and heart rate monitors. Even though these gadgets provide the impression that they will be beneficial, they could be unpleasant and disturbing because they require sensors to be placed on the body of the worker (Yu et al., 2019).

Prediction and Quantification of Fatigue

Limited research has been conducted on the quantification of fatigue. Considering the complexity of measuring mental fatigue, most of these studies have solely focused on physical fatigue. For instance, using simulations, Perez et al. (2014), computed the Maximum Endurance Time (METi) for a laborer performing a physical task. The model would compute the fraction of fatigue (fFi) contribution for each task by dividing the time obtained from the simulation by the Maximum Endurance Time.

$$fF_i = \frac{t_i}{MET_i}$$

Where:

fF_i = the fraction of fatigue (fFi) contribution for task i
t_i = time needed to perform the task i based on the simulation
MET_i = Maximum Endurance Time for task i

In another study, Ferjani et al.(2017), specified how performing a task contributes to an increase in fatigue levels. They assign a difficulty coefficient dj to each machine j to describe the difficulty of work on that machine, such that $0 \leq dj \leq 1$.

The speed of fatigue accumulation is also expressed by this coefficient dj. They introduce Gjθ to characterize how a worker's level of fatigue increases when assigned to machine j for a duration θ, which can be expressed as follows:

$$G_i(\theta) = 1 - e^{-d_j\theta}$$

Where:

Gjθ = worker's level of fatigue
j = type of machine
θ = duration of the task

Management of Construction Workers' Fatigue

The management approaches to handle construction workers' fatigue could be categorized into detection/ prediction and mitigation techniques as shown in figure 2. Detection of fatigue is the primary step in mitigating the outcomes of workers' fatigue. Detection methods were discussed in the previous section. This section reviews some of the techniques used in mitigating fatigue for construction workers.

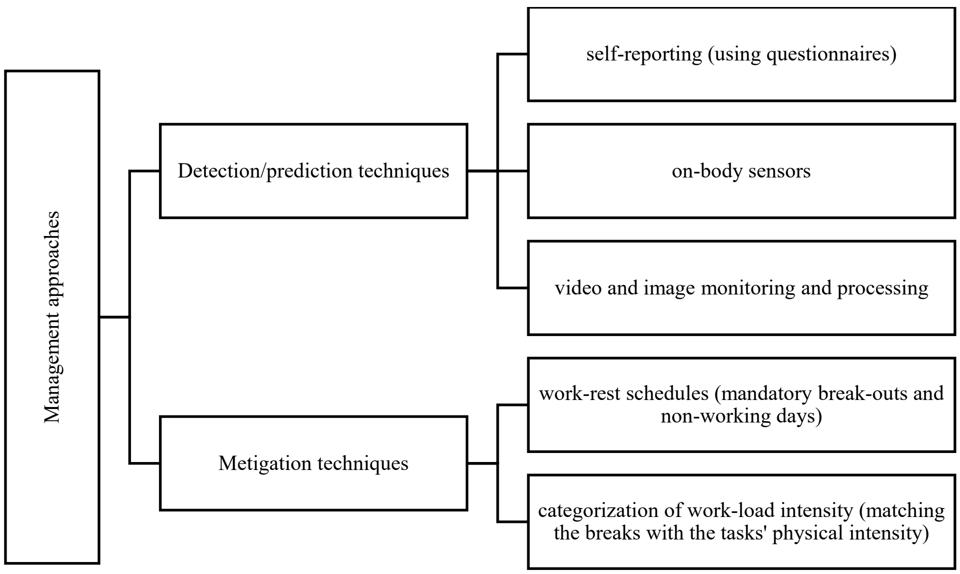

Figure 2. Management approaches to handle the construction workers' fatigue

Personnel scheduling for Construction Fatigue Mitigation

Significant labor issues are jeopardizing the continuous growth of the construction industry in the coming years. These issues include increasing labor wages, an aging workforce, and a lack of personnel in the workforce. Without addressing construction workers' fatigue, it can be expected that labor-related issues exacerbate. Scheduling the work to mitigate fatigue could serve as a motive to improve the willingness and morale of workers to join or stay in this industry.

Fatigue, and particularly its physical type, has close ties with how intensively workers must work, the duration of continuous work, and how break times and nonworking days are scheduled. By studying these links more effective schedules that can contribute to mitigating worker's fatigue can be developed. In doing so, based on prior sleep patterns (Dawson & McCulloch, 2005) devised a methodology to assess fitness for duty. According to the prior sleep/wake model (PSWM), if a worker's shift lasts longer than the quantity of sleep, they received in the previous 48 hours from the time they woke up, they are more likely to make mistakes. The same study also found that in order to be at least minimally fit, a worker must have at least 5 hours of sleep the day before work and 12 hours in the night before. The research efforts in this area seem to be limited and more empirical examinations to assess the impacts of work-rest schedules on mitigating fatigue and boosting workers' productivity are recommended.

Since physical fatigue is highly dependent on the load and intensity of the construction tasks, using universal work shifts for all construction laborers with various levels of physical intensity is questionable. Additionally, the high tendency in the construction industry to complete tasks at faster rates is in contrast with the idea of enforcing break-out intervals to prevent laborer fatigue since the breaks will reduce the project's delivery speed. Identifying a physical-intensity score, particularly for hazardous construction tasks, such as working at heights, can be tested in empirical studies and if proven effective, they can be mandated through construction regulations.

Existing gaps in Managing Construction Fatigue

Even though many researchers agree that fatigue is a major cause of accidents, it is rarely mentioned in injury reports and is usually not talked about until a major accident happens in the industry (Reiner and Krupinski 2011). The current body of information regarding fatigue remains fragmented and confused. Researchers have concentrated on diverse facets of exhaustion, gaining a deeper grasp of specific components, but the scientific community as a whole does not share a common concept of fatigue. In addition, according to our research, very few studies have compared the many causes and effects of fatigue; hence, it is difficult to determine the relative relevance of these causes and effects. This significantly lowers the industry's capacity to effectively manage fatigue.

There are five central gaps in the literature focusing on fatigue in construction projects: 1) Fragmented and various definitions of fatigue in the industry, 2) clear comparison of the causes and effects of fatigue in the workplace, 3) Objective quantification of the impact of fatigue's causes and effects, 4) empirical studies on the various construction trades, 5) an accurate and reliable method for measuring and predicting construction worker fatigue (Techera, 2017).

All of the fatigue causes that have been examined provide means for objective assessment and prediction. Based on the current level of knowledge, objectifying and quantifying these parameters at the same time should result in powerful predictive models. The ability to manage and regulate the onset of fatigue would be improved if a system could be developed to objectively forecast the possibility of exhaustion before work even starts (Techera et al., 2018).

To validate predictors, fatigue must be quantified as a dependent variable (predictand) using cutting-edge techniques. On fatigue measurement, there is a vast and abundant corpus of literature. Given the physiological complexity of weariness, there is no consensus regarding its measurement. Thus, researchers have relied on surrogates for weariness, frequently viewing it as a result of its causes (e.g., workload) and effects (e.g., moving slowly).

The indirect outcomes of fatigue, require more research to assess possible links between fatigue and safety perception and hazard recognition. Research studying the impacts of fatigue has significant overlaps with the studies focusing on multitasking, ergonomics, and the connection between scheduling and productivity. This creates a potential for multidimensional studies that combine the impact of fatigue, particularly those that are more relevant to construction projects. Also, the possible impacts of mitigation methods, such as 1) work-rest schedules (mandatory break-outs and non-working days), and 2) categorization of work-load intensity (matching the breaks with the tasks' physical intensity) needs further empirical studies for assessment. If these studies can show the effectiveness of these measures, mandating them through construction codes and standards should be pursued.

Summary and Conclusion

High physical demands and harsh work situations are one of the root causes of construction accidents. Fatigue is a major contributor to occupational injuries and fatalities, especially in physically intensive tasks. Despite the plethora of research on the topic, fatigue knowledge is dispersed and disorganized. Researchers have concentrated on different components of fatigue to gain greater knowledge, but no overarching explanation exists. Due to a lack of rigorous methods for real-time fatigue monitoring, it is difficult to quantify the direct effects of tiredness on construction safety, resulting in a paucity of fatigue-related studies in occupational safety studies. This hinders the industry's ability to control fatigue. Effective fatigue management strategies for construction workers are an immediate necessity if we are to enhance the way safety is managed on construction sites. Effective fatigue management strategies for construction workers are an immediate necessity if we are to enhance the projects' safety. A proper assessment of fatigue aids in decreasing worker injuries and minimizing associated expenses, as well as in establishing suitable work-rest schedules and shift designs.

References

Al-Bayati, A. J., Tafazzoli, M., York, D. D., & Umar, T. (2020). Cyclical construction workforce shortage: an evaluation of the current shortage in Western North Carolina.

Al-Bouwarthan, M., Quinn, M. M., Kriebel, D., & Wegman, D. H. (2019). Assessment of heat stress exposure among construction workers in the hot desert climate of Saudi Arabia. Annals of work exposures and health, 63(5), 505-520.

Aryal, A., Ghahramani, A., & Becerik-Gerber, B. (2017). Monitoring fatigue in construction workers using physiological measurements. Automation in Construction, 82, 154-165.

Beckers, D. G., Van der Linden, D., Smulders, P. G., Kompier, M. A., Taris, T. W., & Geurts, S. A. (2008). Voluntary or involuntary? Control over overtime and rewards for overtime in relation to fatigue and work satisfaction. Work & Stress, 22(1), 33-50.

Bültmann, U., Kant, I. J., Schröer, C., & Kasl, S. (2002). The relationship between psychosocial work characteristics and fatigue and psychological distress. International archives of occupational and environmental health, 75(4), 259-266.

Chang, F. L., Sun, Y. M., Chuang, K. H., & Hsu, D. J. (2009). Work fatigue and physiological symptoms in different occupations of high-elevation construction workers. Applied ergonomics, 40(4), 591-596.

Cheng, T., Migliaccio, G. C., Teizer, J., & Gatti, U. C. (2013). Data fusion of real-time location sensing and physiological status monitoring for ergonomics analysis of construction workers. Journal of Computing in Civil engineering, 27(3), 320-335.

Dall'Ora, C., Ball, J., Recio-Saucedo, A., & Griffiths, P. (2016). Characteristics of shift work and their impact on employee performance and wellbeing: A literature review. International journal of nursing studies, 57, 12-27.

De Vries, J., Michielsen, H. J., & Van Heck, G. L. (2003). Assessment of fatigue among working people: a comparison of six questionnaires. Occupational and environmental medicine, 60(suppl 1), i10-i15.

Fang, D., Jiang, Z., Zhang, M., & Wang, H. (2015). An experimental method to study the effect of fatigue on construction workers' safety performance. Safety science, 73, 80-91.

Ferjani, A., Ammar, A., Pierreval, H., & Elkosantini, S. (2017). A simulation-optimization based heuristic for the online assignment of multi-skilled workers subjected to fatigue in manufacturing systems. Computers & Industrial Engineering, 112, 663-674.

Gatti, U. C., Schneider, S., & Migliaccio, G. C. (2014). Physiological condition monitoring of construction workers. Automation in Construction, 44, 227-233.

Hallowell, M. R. (2010). Worker fatigue: Managing concerns in rapid renewal highway construction projects. Professional safety, 55(12), 18-26.

Hsu, D. J., Sun, Y. M., Chuang, K. H., Juang, Y. J., & Chang, F. L. (2008). Effect of elevation change on work fatigue and physiological symptoms for high-rise building construction workers. Safety science, 46(5), 833-843.

Jebelli, H., Seo, J., Hwang, S., & Lee, S. (2020). Physiology-based dynamic muscle fatigue model for upper limbs during construction tasks. International Journal of Industrial Ergonomics, 78, 102984.

Jiao, K., Li, Z., Chen, M., Wang, C., & Qi, S. (2004). Effect of different vibration frequencies on heart rate variability and driving fatigue in healthy drivers. International archives of occupational and environmental health, 77(3), 205-212.

Kirk, P. M., & Sullman, M. J. (2001). Heart rate strain in cable hauler choker setters in New Zealand logging operations. Applied Ergonomics, 32(4), 389-398.

Krause, N., Lynch, J., Kaplan, G. A., Cohen, R. D., Goldberg, D. E., & Salonen, J. T. (1997). Predictors of disability retirement. Scandinavian journal of work, environment & health, 403-413.

Lewis, G., & Wessely, S. (1992). The epidemiology of fatigue: more questions than answers. Journal of epidemiology and community health, 46(2), 92.

Merlino, L. A., Rosecrance, J. C., Anton, D., & Cook, T. M. (2003). Symptoms of musculoskeletal disorders among apprentice construction workers. Applied occupational and environmental hygiene, 18(1), 57-64.

Mohamed, S., & Srinavin, K. (2002). Thermal environment effects on construction workers' productivity. Work Study.

Namian, M., Taherpour, F., Ghiasvand, E., & Turkan, Y. (2021). Insidious Safety Threat of Fatigue: Investigating Construction Workers' Risk of Accident Due to Fatigue. Journal of construction engineering and management, 147(12), 04021162.

NSC (2018). How you could pay the price for exhausted employees. Report, Available at: https://www.construction business owner.com/cost-fatigue.

O'Neill, C., & Panuwatwanich, K. (2013). The impact of fatigue on labour productivity: case study of dam construction project in Queensland. Proceedings from EPPM.

Perez, J., De Looze, M. P., Bosch, T., & Neumann, W. P. (2014). Discrete event simulation as an ergonomic tool to predict workload exposures during systems design. International Journal of Industrial Ergonomics, 44(2), 298-306.

Powell, R., & Copping, A. (2010). Sleep deprivation and its consequences in construction workers. Journal of construction engineering and management, 136(10), 1086-1092.

Reiner, B. I., & Krupinski, E. (2012). Demystifying occupational stress and fatigue through the creation of an adaptive end-user profiling system. Journal of digital imaging, 25(2), 201-205.

Rosekind, M. R., Gregory, K. B., Mallis, M. M., Brandt, S. L., Seal, B., & Lerner, D. (2010). The cost of poor sleep: workplace productivity loss and associated costs. Journal of Occupational and Environmental Medicine, 91-98.

Swaen, G. M. H., Van Amelsvoort, L. G. P. M., Bültmann, U., & Kant, I. J. (2003). Fatigue as a risk factor for being injured in an occupational accident: results from the Maastricht Cohort Study. Occupational and environmental medicine, 60(suppl 1), i88-i92.

Tafazzoli, M., & Shrestha, P. (2017, October). Factor analysis of construction delays in the US construction industry. In International conference on sustainable infrastructure (pp. 111-122).

Tafazzoli, M., Kermanshachi, S., Shrestha, K., & Kisi, K. (2020, November). Investigating the relative importance barriers to sustainable construction related to owners, contractors, and government. In Construction Research Congress 2020: Infrastructure Systems and Sustainability (pp. 341-350). Reston, VA: American Society of Civil Engineers.

Techera, U. D. (2017). Measuring and managing construction worker fatigue (Doctoral dissertation, University of Colorado at Boulder).

Techera, U., Hallowell, M., Stambaugh, N., & Littlejohn, R. (2016). Causes and consequences of occupational fatigue. Journal of occupational and environmental medicine, 58(10), 961-973.

Tixier, A. J. P., Hallowell, M. R., Albert, A., van Boven, L., & Kleiner, B. M. (2014). Psychological antecedents of risk-taking behavior in construction. Journal of construction engineering and management, 140(11), 04014052.

U.S. Bureau of Labor Statistics, Nonfatal Occupational Injuries and Illnesses Requiring Days Away From Work, (2016). https://www.bls.gov/news.release/osh2.toc.htm (accessed October 29, 2022).

Van der Hulst, M., & Geurts, S. (2001). Associations between overtime and psychological health in high and low reward jobs. Work and stress, 15(3), 227-240.

Xing, X., Li, H., Li, J., Zhong, B., Luo, H., & Skitmore, M. (2019). A multicomponent and neurophysiological intervention for the emotional and mental states of high-altitude construction workers. Automation in Construction, 105, 102836.

Xing, X., Zhong, B., Luo, H., Rose, T., Li, J., & Antwi-Afari, M. F. (2020). Effects of physical fatigue on the induction of mental fatigue of construction workers: A pilot study based on a neurophysiological approach. Automation in Construction, 120, 103381.

Historic Building Case Study: Measuring Differential Settlement Combined with Experiential Learning

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Sagging floors along with cracked interior finishes and exterior masonry is commonplace for structures that have been in service for an extended period of time. Differential settlement is a phenomenon that many structures undergo. A historical building society had a building that was over 150 years old and was experiencing the aforementioned distresses. Wanting a second opinion they called a local university for their expertise and help. The faculty decided this project would be a great opportunity for an undergraduate construction science student to interact with a client and develop a solution. The project led to a great experiential learning opportunity for one student. The student was able to interact with a client and come up with real world solutions, just like they would have to endure once in industry. The student had to determine what was causing the cracking and find a way to prove if there were immediate safety concerns for the building. In the end everyone benefited from the project as the historical building society received a valuable second opinion and an undergraduate student found practical uses for ideas to solve problems and make decisions based on the findings.

Key Words: Differential Settlement, Experiential Learning, Historical Building, Assessment Report, Undergraduate Research

Introduction

What happens when the president of an historical building society in rural North America think they have rapid settlement and foundation concerns for a building initially constructed in the 1860's? In this instance the president called a local contractor who proposed expensive foundation and subflooring repairs and sold the building society that these repairs needed to be made immediately. The building society was convinced that the interior and exterior wall cracking and sagging floors were deteriorating rapidly by the day. They were convinced that the unevenness of the walls and floors, Figure 1, were getting worse by the day and not a result of long-term settlement and natural aging of the building. The building society wanted to get a second opinion prior to performing these expensive repairs. However, being in rural America they did not have many options. Thus, they called a local university that had an engineering and construction program to see if they could perform a review of the building and provide opinions. Several faculty members agreed to take on the project. They saw this as an opportunity to not only provide help to the historical building society but also as an experiential learning opportunity for an undergraduate student in the construction science program. The student would have the opportunity to interact with the client, perform an onsite assessment, and prepare a written report for a client. The scope of the project entailed determining if the perceived settlement and interior finishes cracking were all an immediate concern or if the cracking and sagging floors were natural for a building of this age. Upon completion of the assessment, a final written report would be prepared for the historical building society.

Figure 1. Plumbness of header above doorway

Literature Review

The traditional lecture mode of teaching in the college classroom has shifted over the past few decades. The days of instructors lecturing and students taking notes the entire class period are being replaced with active learning and cooperative learning. Active learning is one that replaces the traditional method of relying solely on the instructor's lectures and introducing any activity that engages the student in critical thought. Dewey foresaw what employers and graduates see today, the need for general intellectual and analytical skills (problem-solving) through practical "hands-on" training (Davies et al., 1999). Much research on the topic of active learning has been completed over the last several decades as evidenced by both Faust and Paulson (1998) and Sims (1995) to just name a few. A simple internet search will result in numerous studies on the topic of active learning. Faust and Paulson (1998) define active learning as "any activity engaged in by students in a classroom other than listening passively to an instructor's lecture." As they conclude: "Active-learning techniques…are those activities that an instructor incorporates into the classroom to foster active learning." In short, anything other than passively listening to an instructor's lecture.

Many examples exist on what some would classify as active learning. One-minute papers, think-pair-share, skeleton style notes, field trips, cooperative learning, flipped classroom, and experiential learning are just a few of the active learning techniques that are being used in the classroom as evidenced by Faust and Paulson (1998). There are many branches of constructivist although most all denominations agree with the basic principle "learning is not a passive receiving of ready-made knowledge but a process of construction in which the students themselves have to be the primary actors" (Von Glasersfeld, 1995). Experiential learning is an active learning technique that has been cited many times. Kolb (1984) defines experiential learning as “the process whereby knowledge is created through the transformation of experience.” One learns new knowledge through four different modes; concrete experience, abilities, reflective observation abilities, abstract conceptualization abilities, and active experimentation (Kolb 1984). Lee et al. (2008) took the four learning modes and styles of experiential learning and applied them to the experiential learning process. They did this at both a macro and micro level. One of the major findings was that there was a positive correlation between the implementation of the aforementioned four modes of experiential learning and students learning.

A study (Stice 1987) of the retention of knowledge showed 20% retention when only abstract conceptualization was used. Stice further indicated as more of the Kolb’s modes are used, the retention rate increased. The study also shows a 90% retention when all four modes are used, concrete experience, abilities, reflective observation abilities, abstract conceptualization abilities, and active experimentation. These are the four building blocks used during the undergraduate research.

What is Experiential Learning

When discussing practice theory, often Sophocles’ is often quoted from 400 B.C., “one must learn by doing the thing, for though you think you know it, you have no certainty until you try”, (Gentry 1990). Undergraduate research is one method of experiential learning. Bresnen (2009) postulated that practice theory has been offered as a useful approach for investigation of actual work practices. Another step to practice theory is the pedagogy of project-based learning. This style of learning is action based and allows the student to put the classroom instruction to practical use as noted by Figgess (2017). The faculty focused on using Kolb’s four modes of learning while working with the student to assist in all aspects as well as knowledge retention. In this particular research the student experienced both the hard skills for monitoring the differential settlement as well as the soft skills for dealing with a client.

What is Differential Settlement

The behavior of differential settlement for a building is influenced by the soil beneath the structures foundations, (Lahri, 2015). This is especially true with historical buildings due to the decades of soil settlement and freeze thaw cycles. If this settlement is uniform there is no impact on the building structure. However, when the building experiences non-uniform, or differential settlement damage often occurs to the structure (Lahri, 2015). This depends on many factors such as the type and loading of the structure, soil conditions, and the rigidity of the building frame (Arapakou & Papadopoulos, 2012). Additionally, a historic building often has renovations and additions throughout its life, which may increase the likelihood of non-uniform settlement. Determining the cause of differential settlement can be challenging. Common causes are “expulsion of water from the soil mass, flooding, frost heave…tree root systems and inappropriate foundation designs” (Lahri, 2015). Often the issue is determining whether the settlement is continuing, or has ran its course. There are a myriad of tools for monitoring the settlement of a building. The most common measuring technique is determining movement of cracking with electronic or analog equipment and leveling instruments (Rossi, 2001).

Ways to Measure Differential Settlement

The authors decided the best way to measure any settlement would be with a zip level. A zip level is a high precision pressurized hydrostatic altimeter (Corporation 2022), Figure 2. Spot elevations can be measured at various locations and compared to a zero-elevation datum. Then future measurements can be made and compared to the original measurements to see the magnitude of settlement. The zip level was advantageous as only one person is needed to operate, which was carried out by the undergraduate student. The authors determined that any short-term settlements under 0.5-inches could be attributed to tolerance of the zip-level or spot elevations not taken directly in the same exact location. Any change in elevation over 0.5-inches would be considered extreme and constitute settlement at a rate that would be unsafe for the building.

Figure 2. Zip level used for elevation change measurements

Project Background

Ellsworth Building

Ellsworth, Kansas, is a small town located in the central portion of the state. In the late 1860's during the Kansas Pacific Railroad period, the town became popular by operating a major stockyard for all cattle entering town to then be shipped to eastern markets. During the years 1874 through 1876, Ellsworth experienced unexpected and detrimental fires to the town which consumed many residences and other buildings on both north and south Main streets. To avoid any more damaging fires, Perry and Phoebe Hodgen owned the first private home with a stone exterior in 1876, Figure 3. The famous and historic Hodgen House is located between the Smokey Hill River and the towns historic railroad tracks. Even though the historic house still stands tall amongst the Ellsworth community, there lies concerns of foundation settlement issues that may cause further problems if not serviced.

The Hodgen House was built in 1876 with many additions that were to follow over the next few years. The original structure of the house is a two-story wood frame building that sits upon a rock foundation along with a stonework exterior which was later added around 1878. In 1879, a one-story addition was built along the East backside of the house which consisted of two additional rooms to the house. The following year in 1880, there was a second floor constructed above the East addition that included another two rooms to the household. In 1882, a two-story addition was constructed on the West backside that included four more additional rooms. Aside from other improvements to the house that come in later years, approximately six years of construction transpired to develop the full structure of the house as it is today.

Figure 3. Hodgen House on North East elevation

Experiential Learning

The undergraduate student was responsible for interacting with the client by using soft skills that were further developed in many classes throughout their undergraduate studies. This included setting up site visits and learning about the history of the building. Technical (hard) skills were needed to complete the survey and determine if the building was undergoing short-term settlement. The student had to research the best way to measure any settlement and determined the best course of action for that would be with the use of wall mounted strain gages and the aforementioned zip level. At the end of the project the student was responsible to preparing an assessment report for the client and verbally delivering the results to the client.

Initial Survey

The Hodgen House was first visited on September 28th, 2021 and the initial observations noted were cracks found on a few walls as well as the slopping and sagging floors seen throughout the house. Figure 4 shows the typical sagging floor at room entry thresholds.

Figure 4. Typical floor conditions

During this visit, strain gages were installed on two wall crack locations. Figure 5A shows the strain when it was first installed with the cross-hairs near the zero-zero intersection. On January 26th, 2022, observation of the same strain gage was captured to investigate if there was any difference or comparison of when it was first installed shown in Figure 5B. The results were to determine if there is to be any widening of those cracks occurring over time as the cross-hairs are still near the zero-zero intersections. It can be seen from these figures (5A & 5B) that negligible movement occurred and short-term settlement was not occurring at a noticeable rate.

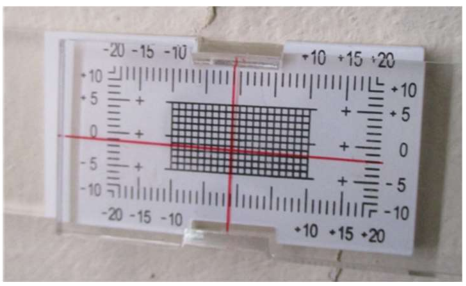

Figure 5A. Strain gage 1 on Sept 28, 2021

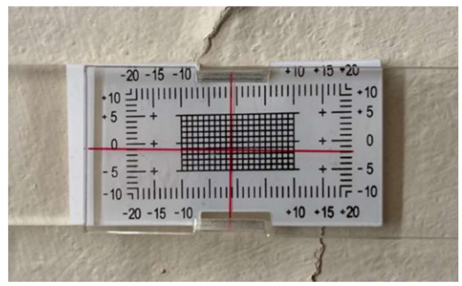

Figure 5B. Strain Gage 1 on Jan 26, 2022

Data Collection

On November 13th, 2021, a zip level was utilized to measure floor elevations throughout the Hodgen House. A zip level is a measuring tool that calculates elevation differences from a known benchmark (indicated by the red dot in Figure 6). The zip level measured elevations at different locations throughout the house to determine exactly how much the floor elevations had changed over a given time frame. After determining the floor elevations at approximately four-foot increments throughout the first floor, a survey map was designed to display the high and low areas within the house. The total difference between the highest and lowest recorded elevation points calculated to a value of 5.5 inches. On March 3, 2022, the zip level was used for a second time to collect another set of elevation points to then compare those values to the original data. In the second survey map, the total difference between the highest and lowest locations calculated of 5.7 inches which is a 0.2-inch increase from the first survey. Refer to Figure 6 to view the survey elevation maps conducted on November 13, 2021, and March 3, 2022.

Conclusions and Discussion

Results

After observing the strain gages installed at the set locations compared to when they were first installed, there is a near zero difference between the two periods. Therefore, the data from the strain gages indicates there has not been any significant movement within those wall crack locations in the four months after being installed and recording data. From the conducted floor elevation observations that transpired before and after the winter season, a net change map was created to determine how much the building's foundation moved within those few months.

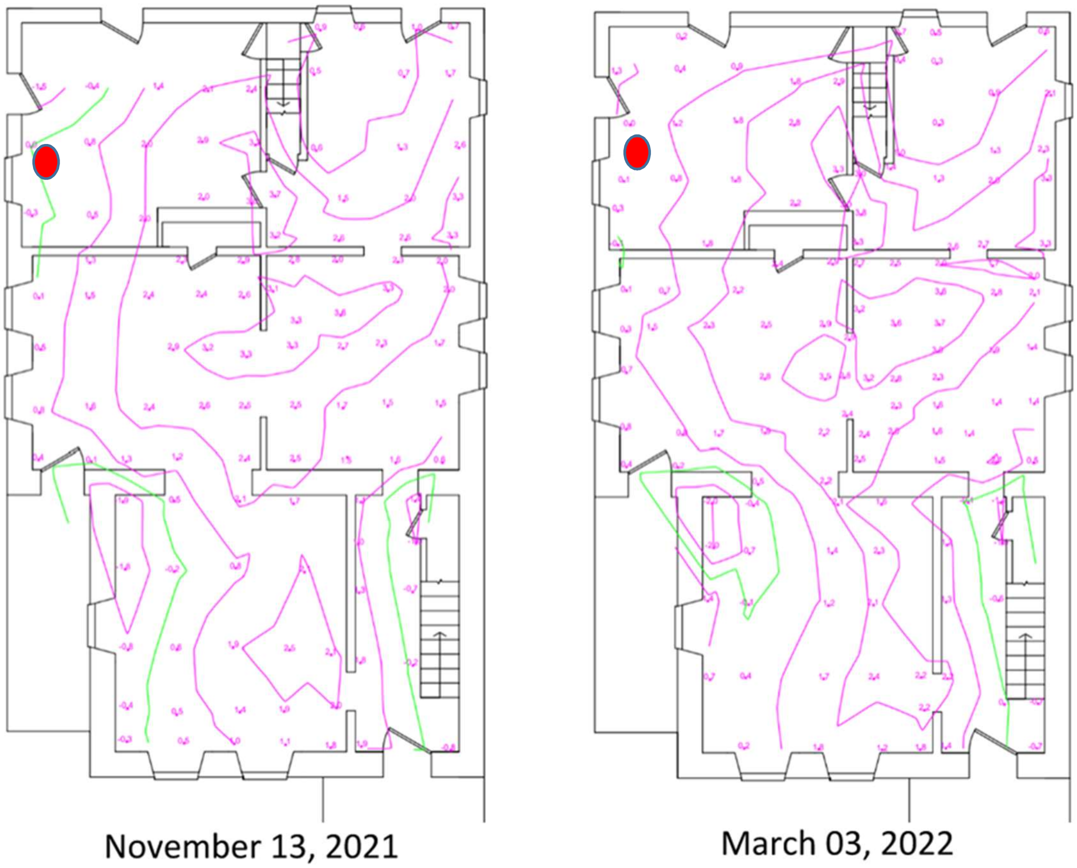

Figure 6. Survey Elevation Maps

Figure 7 shows the net changes in elevations off an absolute value. According to the data observed, there was not a floor elevation change larger than half an inch and that occurred in a few isolated locations. The lack of large deflections indicates there was very little movement within the structure that took place. Slight movement in a building is typical since numerous freeze-thaw cycles can occur in a short period of time. Regardless of a building's age, experiencing settlement is inevitable to happen. Additionally, due to its age, differential settlement is common to occur. Due to the lack of large net elevation changes greater than 0.2-inches in the 4-month period between readings the building is not undergoing rapid settlement, rather the building has experienced long-term differential settlement. Thus, the sagging floors and cracked finishes are not an immediate concern but should be repaired from both a moisture intrusion and serviceability standpoint.

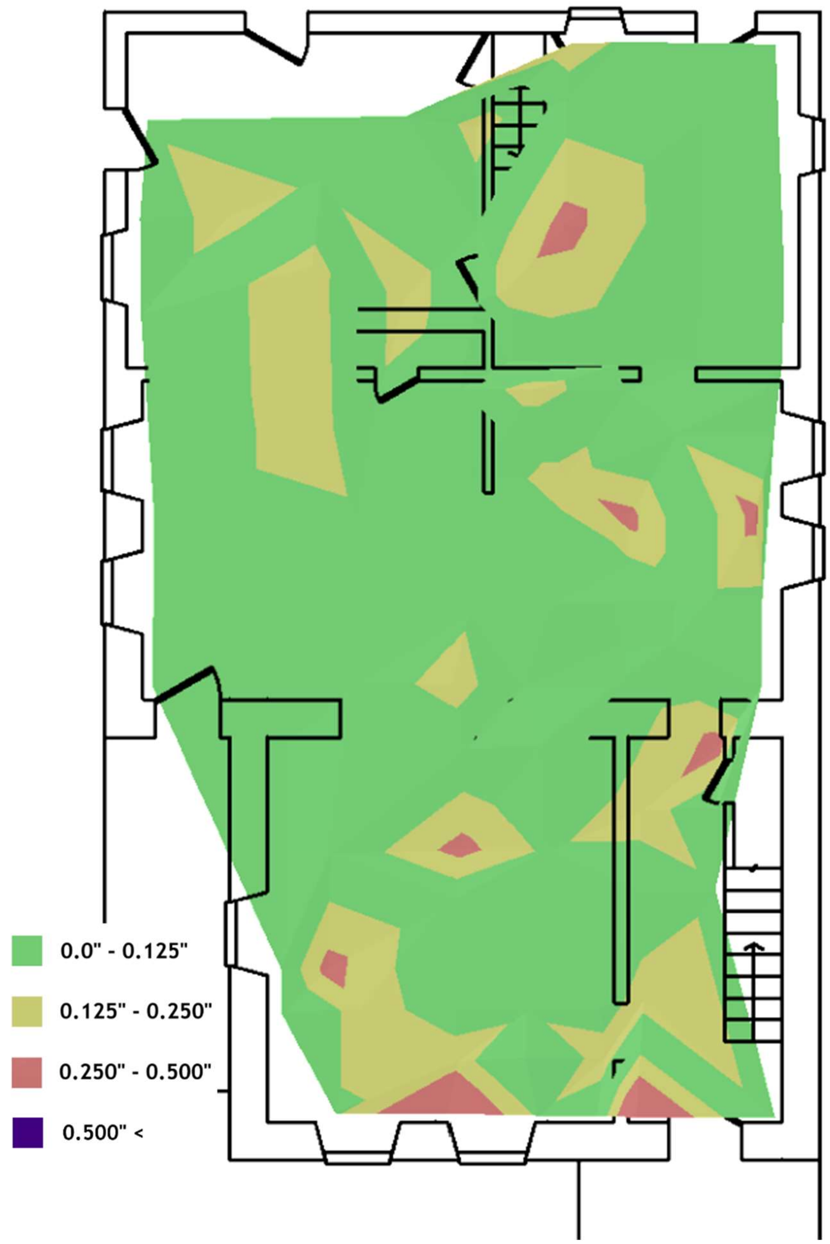

Figure 7. Net change in elevation of first floor

Experiential Learning Results

"Tell me, and I will forget. Show me and I may remember. Involve me, and I will understand." This is a famous quote that many have attributed to Benjamin Franklin or Confucius. It can also explain the importance of active learning as opposed to passively sitting in the back of a classroom listening to an instructor lecture for class periods on end. Through this research, the student gained experience in both hard and soft skills by actively learning. The student was presented with a problem, from a specific client, collected data, analyzed the data and developed a finding. Additionally, the student interacted with the client, using and developing soft skills. This entire research project helped to prepare the student for a career in construction management. Using the four modes of experiential learning the faculty determined the student found practical uses for ideas to solve problems and make decisions based on the findings.

References

Arapakou, A. E., & Papadopoulos, V. P. (2012). Factors Affecting Differential Settlements of Framed Structures. Geotechnical and Geological Engineering, 30(6), 1323-1333. https://doi.org/10.1007/s10706-012-9546-x

Bresnen, M. (2009). Learning to co-operate and co-operating to learn: knowledge, learning and innovation in construction supply chains. Construction Supply Chain Management: Concepts and Case Studies, 73-91.

Coporation, T. M. (2022). Products overview. https://www.ziplevel.com/products_overview

Davies, H., Csete, J., & Poon, L. (1999). Employer's expectations of the performance of construction graduates. *International Journal of Engineering Education, 15*(3), 191-198.

Faust, J. L., & Paulson, D. R. (1998). Active learning in the college classroom. *Journal on excellence in college teaching*, *9*(2), 3-24.

Figgess, G. W. (2017). Building Career-Ready Students through Multidisciplinary Project-Based Learning Opportunities - A Case Study 2017 ASEE Annual Conference & Exposition, Columbus, OH.

Gentry, J. W. (1990). What is Experiential learning. In Guide to Business Gaming and Experiential Learning (pp. 20).

Kolb, D.A. (1984). Experiential learning: Experience as the source of learning and development. Prentice Hall. Englewood Cliffs, N.J., 1-38.

Lahri, A. (2015). Effect of differential settlement on frame forces-A parametric study. International Journal of Research in Engineering and Technology (4(9)), 453-464.

Lee, J. H., McCullouch, B. G., & Chang, L. M. (2008). Macrolevel and microlevel frameworks of experiential learning theory in construction engineering education. *Journal of Professional Issues in Engineering Education and Practice*, *134*(2), 158-164.

Rossi, C. (2001). A low-cost procedure for quick monitoring of monuments and buildings. On site Control and Evaluation of Masonry Structures, 81-94.

Sims, S. (1995). Experiential learning: Preparing students to move from the classroom to the work environment. *The importance of learning styles*, 147-160.

Stice, J. E. (1987). Using Kolb's Learning Cycle to Improve Student Learning. *Engineering education*, *77*(5), 291-96.

Von Glasersfeld, E. (1995). Learning Mathematics: Constructivist and interactionist theories of mathematical development, Review of the book Learning Mathematics: Constructivist and Interactionist Theories of Mathematical Development, P. Cobb. *Zentralblatt fur Didaktik der Mathematik, 4*, 120-122.

A Review of Social Sustainability Studies Involving Multiple-Criteria within the Construction Industry

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This paper explores future research directions on social sustainability in the construction industry through a systematic literature review of studies focusing on multiple criteria. The analysis involved 36 studies identified through the Web of Science, ScienceDirect, and Scopus. The results uncovered how social sustainability assessment is conducted, and where the studies are taking place, mostly in developing countries. On average, the reviewed studies used 29 criteria to assess social sustainability. That large number of criteria indicates a need to find a subset of criteria capable of representing social sustainability complexity. Regarding the methods identified, Multicriteria Decision-Making/Aiding (MCDM/A) methods are the most used, including the Analytic Hierarchy Process (AHP) and weighted aggregation. However, it is difficult to confirm if they are the most appropriate since the authors did not mention how these methodologies were selected or the decision-makers' rationality, which is necessary for choosing the proper MCDM/A method. Thus, future studies in social sustainability should focus on: i) dimensionality reduction and ii) the structure of the decision problem to correctly choose the decision method. These two recommendations will add to the body of knowledge, especially to the value of integrating the social aspect of sustainability in construction.

Key Words: Social Sustainability, Construction, Projects, Multiple-Criteria

Introduction and Purpose

Social sustainability is one of the three pillars of the triple bottom line of sustainable development, which has been gaining some attention since the Report of the World Commission on Environment and Development: Our Common Future (ONU, 1987). The social aspect of sustainability can be understood as a series of processes to improve the health, safety, and well-being conditions of any person affected directly or indirectly by a construction project during its life cycle (Valdes-Vasquez & Klotz, 2013). However, social sustainability has been taken into consideration less when compared to the other environmental and economic pillars of sustainability (Ahmad & Thaheem, 2017; Sierra, Yepes, & Pellicer, 2018).

This lesser attention to social sustainability is an important area to address in improving the construction industry. Specifically, social sustainability can be considered the pillar responsible for most needs of human well-being (Forsman & Jonsson, 2016), and its implementation provides a potential economic advantage (Marzouk & Sabbah, 2021). Recently, this topic has been increasingly gaining attention in academic discussions (Nasirzadeh et al., 2020), describing the difficulties of reaching a consensus concerning concepts and operationalizing them, by turning abstract conceptual ideas into measurable observations (Shirazi & Keivani, 2019; Vallance et al., 2011). The main obstacle to implementing social sustainability in construction projects is the lack of knowledge about what social sustainability criteria should be included and the high level of subjectivity in prioritizing their importance (Montalbán-Domingo et al., 2020). In addition to these obstacles, it is difficult to quantitatively measure social sustainability compared to the other aspects of sustainability. Especially when considering each country's specific context (McKenzie, 2004).

Some initiatives have arisen to incorporate sustainability in construction. For example, since the 1990s, many green rating systems have been developed to assess sustainability in construction, but they mainly focus on the environmental aspect of sustainability (Sierra, Yepes, & Pellicer, 2018; Zarghami et al., 2019). Therefore, other ways of assessing social sustainability have been developed (Almahmoud & Doloi, 2015; Karji et al., 2019; Mulliner et al., 2013; Olakitan Atanda, 2019). These studies have advanced the body of knowledge by providing methods to assess social sustainability. However, their limitations of coverage and focus require more effort in this direction (Rostamnezhad & Thaheem, 2022).

For example, Gurmu et al. (2022) and Rostamnezhad & Thaheem (2022) investigated which aspects of social sustainability were considered in previous construction studies. Since each of the previous studies consider different facets of social sustainability, the authors recognized that a comprehensive assessment was missing. These researchers identified that the categories encompassed by social sustainability studies in construction are stakeholders, occupational safety and health, human resources, community, socioeconomic compliance, neighborhood, ecological impact, quality of life, diversity, cultural heritage, subcontractors, ethics, and innovation. These studies reinforce the complexity and comprehensiveness of the social aspect of sustainability. Nevertheless, their results did not focus on the methods or criteria used to assess construction projects and their processes.

Given this gap, through a systematic literature review, this paper explores future social sustainability research directions for its operationalization and applicability in assessing construction projects. The review focuses on how social sustainability is evaluated in the construction industry in studies that specify the criteria used. The following four questions are addressed:

- What are the prominent academic journals that discuss criteria used to assess social sustainability in the construction industry, and which countries have most applied them?
- What sources are used for the social sustainability criteria when assessing the construction industry?
- Which methods are used to assess social sustainability in the construction industry?
- What are the opportunities for improvement in assessing social sustainability in the construction industry?

The methodology will be introduced in the following sections. Subsequently, the results and discussions will be presented. Finally, the conclusions and two main recommendations for future research will be provided to enable an efficient assessment of social sustainability in the construction industry.

Methods

This research followed the systematic literature review methodology to enhance the knowledge base and inform practice (Tranfield et al., 2003). This literature review can be classified as a scoping review, which broadly and systematically searches the literature regarding the topic, extracts information from the papers, and synthesizes them. This technique also allows the studies to be placed in a historical and academic context (Xiao & Watson, 2019). The review involves three main phases: planning, conducting, and reporting (Tranfield et al., 2003). The procedure for this research was developed referring to the well-known guidelines of systematic review (Moher et al., 2016). The key steps of the screening process are shown in Figure 1. The search in the databases was conducted with the following keywords: "social sustainability" AND (construction OR buildings OR residential OR infrastructure OR commercial OR industrial). As shown in Figure 1, 222 papers were initially found in the Web of Science database, 513 in Scopus, and 41 in Science Direct, for a total of 776 papers. After the exclusion of duplicates, 572 articles were selected based on the title.

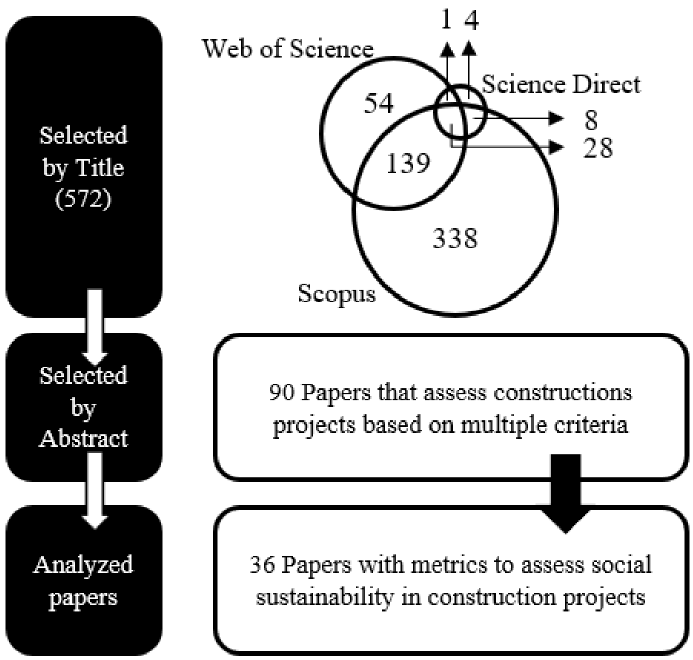

Figure 1. Flowchart for the screening process

Two previous literature reviews were found among the studies addressing social sustainability in construction. These two literature reviews served as a basis for analyzing the extent of social sustainability in construction (Gurmu et al., 2022; Rostamnezhad & Thaheem, 2022). However, they do not examine the metrics used to evaluate the impact of construction, which is fundamental to its operationalization. Thus, 90 papers were identified to quantitatively assess the social sustainability in the construction industry, considering multiple criteria in their assessment. Nevertheless, after reading these papers, some studies were excluded because they did not explicitly bring criteria with metrics, were not applied in a case related to construction, or did not deal exclusively with the social aspect of sustainability. After all the screening, 36 papers were selected for further analysis. The list of analyzed papers is available at: https://tinyurl.com/libraryasc2022.

The following section presents the results and discussions based on the 36 articles selected through a systematic process that addresses the metrics used to evaluate constructions. The results and analysis were cross-checked among the authors, and the conclusions were based solely on systematically selected papers. First, a descriptive analysis of the studies is presented, emphasizing the prominent journals discussing social sustainability assessment with explicit metrics and the leading countries evaluating social sustainability. Then, how this evaluation is being conducted will be discussed.

Results and Discussion

Descriptive Analysis of the Selected Papers

As illustrated in Figure 2, four journals account for more than half of the publications that provide metrics for the evaluation of social sustainability in construction projects: Journal of Cleaner Production (six), Sustainability (Switzerland) (five), Sustainable Cities and Society (four), and Environmental Impact Assessment Review (four). Regarding the countries, Table 1 shows in which countries the studies have applied the assessment methods for social sustainability.

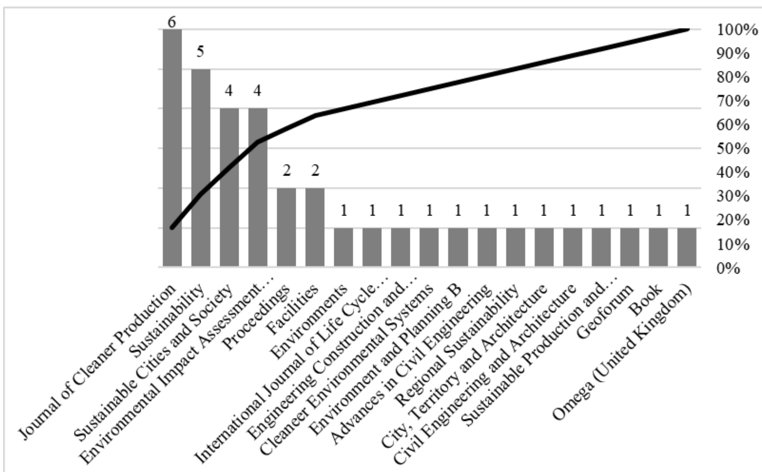

Figure 2. Journals where the analyzed studies were published

Table 1

Location of studies assessing social sustainability

Classification*	Number of studies	Country
Developing Countries	5	Iran
	4	China
	3	El Salvador
	6 (2 in each)	Hong Kong, Jordan, and United Arab Emirates
	9 (1 in each)	Taiwan, Singapore, Egypt, Ethiopia, Nigeria, Pakistan, Saudi Arabia, Vietnam, and Malaysia
Developed countries	4 (1 in each)	Cyprus, Hungary, New Zealand, and the United Kingdom

*Classification according to the United Nations Department of Economics et al. (2022)

According to Table 1, 27 studies were applied in developing countries, while only four were applied in developed countries. The authors based the classification on the United Nations Department of Economics et al. (2022). Specifically, in developing countries, Sierra et al. (2018) selected 21 criteria to assess a set of alternatives for road infrastructure projects in El Salvador, and Karji et al. (2019) used 33 indicators to determine the social sustainability of the Mehr Housing Project in Iran. Whereas in developed countries, for example, Olukoya & Atanda (2020) selected 37 criteria to assess four architectural typologies in a village in Cyprus, and Mulliner et al. (2013) used 20 criteria to assess three residential neighborhoods in Liverpool, UK. Thus, Table 1 shows that 87% (27/31) of the studies have been performed in developing countries. The main reason for this could be that developing countries have been working to make interventions considering these aspects. On the other hand, in developed countries, the concept of recognizing the rights of neighbors, neighbors, and employers is more deeply rooted (VillarinhoRosa & Haddad, 2013).

Social Sustainability Assessment

Figure 3 shows the source of the social sustainability criteria used and which part of the construction industry they are applied to. In particular, Figure 3a displays most studies use social sustainability criteria from a literature review and expert judgment. A total of 21 studies use more than one source, and 11 combine criteria selection from some documentation with a subsequent screening process by experts. Regarding the green rating systems, the most used references are LEED (five), followed by BREEAM (two), and CASBEE (two).

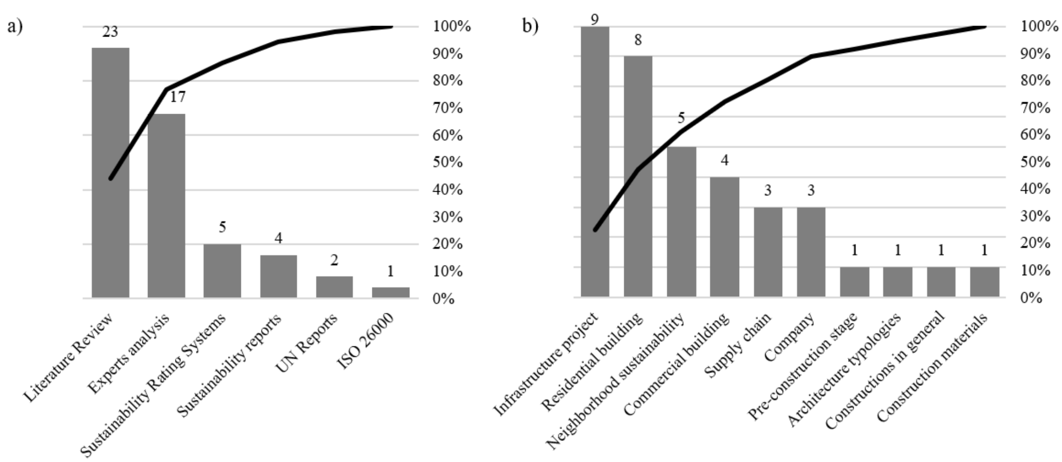

Figure 3a. Data source. 3b. Focus of the study related to construction.

Figure 3b shows that social sustainability criteria have been used to evaluate infrastructure projects and residential buildings. Five of the 36 studies discussed criteria without implementation and 31 developed case studies. In the case studies analyzed, each construction alternative was assessed, on average, according to 29 different criteria. The work of Hendiani & Bagherpour (2019), for example, used 71 different criteria, aggregating them additively. On the other hand, the study by Petrudi et al. (2021) used the fewest criteria (seven). However, their study could have explained how this subset of criteria would effectively represent the complexity of the social aspect of sustainability. Most likely, this considerable amount of criteria generally used by previous studies may be due to the complexity and comprehensiveness of the stakeholders and factors related to social sustainability (Gurmu et al., 2022; Rostamnezhad & Thaheem, 2022). Furthermore, such issues can be applied to different project phases, as well as to different project types (e.g., residential, commercial, and infrastructure) and, finally, to other location contexts (e.g., neighborhood, region, and country), as shown in Figure 4.

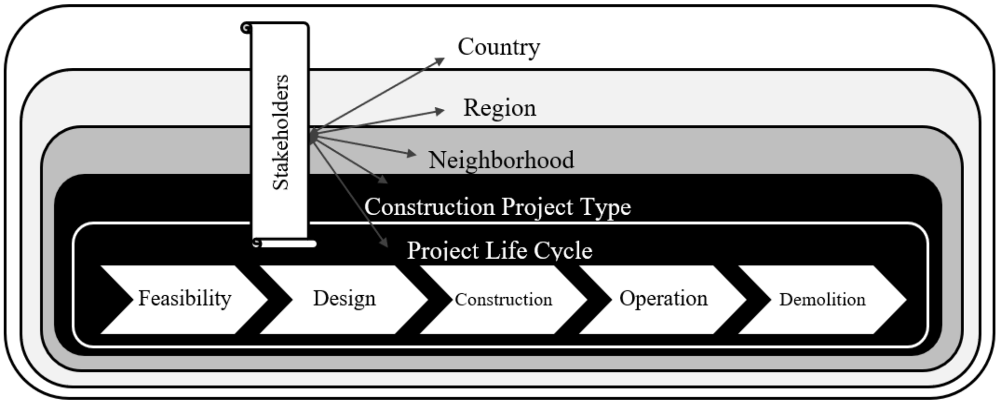

Figure 4. The extent and complexity of social sustainability in the construction industry.

However, this large number of criteria used to represent this complexity makes the evaluation very difficult and subjective. Moreover, according to Roselli & de Almeida (2021), the more criteria used, the lower the probability of decision-making success. Therefore, there is a high risk of failure when seven criteria or more are used. One possible implication of this is that the applicability of social sustainability depends on a reduction of the dimensionality of the problem. Therefore, finding a subset of criteria that can represent the complexity of this aspect of sustainability is a big challenge on which efforts must be concentrated. Regarding the analytical methods used, Table 2 shows the ones used in these 36 studies. Most studies use Multicriteria Decision-Making/Aiding Methods (MCDM/A) to select the alternatives, but statistical analysis, multi-objective algorithms, and others are also used to assess different alternatives.

Table 2

Methods to assess social sustainability

Classification	Method	Quantity	Total
Multicriteria Decision Method	Analytic Hierarchy Process (AHP)	10	23
	Weighted Aggregation	7	
	DEMATEL	1	
	TOPSIS	1	
	Analytic Network Process (ANP)	1	
	Best Worst Method (BWM)	1	
	PROMETHEE	1	
	COPRAS	1	
Statistical Analysis	Cluster Analysis	3	6
	Factor Analysis	2	
	One-way Statistical Analysis (ANOVA)	1	
Multi Objective Algorithm	Harmony Search Algorithm	1	4
	Pareto Border	1	
	Euclidean Distance	1	
	Chebyshev Distance	1	
Others	Data Envelopment Analysis (DEA)	1	3
	Social Network Analysis (SNA)	1	
	System Dynamics	1	

It is worth noting that some studies combine different methods while others do not use any method; they only evaluate the alternative concerning the selected criteria. That tendency for aggregation may also be due to the large number of criteria used to assess the alternatives in construction. In terms of MCDM/A, most studies (74%) use either the Analytic Hierarchy Process (AHP) or Weighted Aggregation to decide their studies, which are methods of compensatory rationality in which a worse performance on one criterion can be compensated for by better performance on another (Stewart, 1992). Nevertheless, researchers have not explored the justification for the method used or put any effort into structuring the decision problem.

Therefore, strategies to enhance the evaluation of social sustainability in construction projects involve exploring the structuring of the problem as well as the rationality of the decision-maker (de Almeida et al., 2015). Since the choice of multicriteria decision method depends on the decision maker's preference structure and rationality, there is no way to judge whether the methods have been adequately chosen. However, compensatory rationality does not seem to be the most appropriate to use in social sustainability problems since it does not seem to be adequate to compensate for low occupational health and safety performance by improving thermal comfort performance for end users.

Conclusions and Future Research

This paper explores future social sustainability research directions for its operationalization and applicability in the construction industry. To this end, the authors conducted a systematic literature review to identify how social sustainability assessment has been applied. Besides exploring the descriptive character and where and by what means this subject has been discussed, this work presents results that have important implications for future studies in assessing social sustainability in construction.

Initially, the complexity and comprehensiveness of social sustainability in construction were reaffirmed, which does not match the importance given to this aspect of sustainability by green rating systems - around 20% (Abed, 2017). Moreover, this complexity is translated in social sustainability assessments through many criteria in the decision problems, applying the frameworks developed so far difficult. Thus, a crucial strategy to strengthen how to operationalize social sustainability is to reduce the problem's dimensionality by selecting a subset of social sustainability criteria that can represent the problem efficiently. Furthermore, most previous studies used compensatory rationality to decide on the construction industry but still need to discuss structuring the multicriteria decision problem. This lack of specificity in the choice of method can easily lead to wrong decisions or paths. Therefore, future works should explore the structuring of the decision problem and justify the choice of method to assess social sustainability, highlighting the rationality of the decision maker (compensatory or non-compensatory), as well as their preference structure.

Future work can attempt to operationalize the social aspect of sustainability in construction by structuring the decision problem to correctly choose the method, and use fewer criteria to assess the alternatives. To address this recomendation, future studies can evaluate which metrics are most used in the frameworks developed. This information is of great value in finding a subset of criteria that can represent the complexity of the problem. In addition, other ways of reducing the problem's dimensionality should also be explored, such as using data-driven and statistical methods to check which criteria provide the most information, eliminating those highly correlated with others. These two strategies of problem structuring, and dimensionality reduction are essential for an efficient operationalization of social sustainability.

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References

Abed, A. R. (2017). Assessment of social sustainability: A comparative analysis. *Proceedings of the Institution of Civil Engineers: Urban Design and Planning*, *170*(2), 72–82. https://doi.org/10.1680/jurdp.16.00020

Ahmad, T., & Thaheem, M. J. (2017). Developing a residential building-related social sustainability assessment framework and its implications for BIM. *Sustainable Cities and Society*, *28*, 1–15. https://doi.org/10.1016/j.scs.2016.08.002

de Almeida, A. T., Alexandre, C., Cavalcante, V., Alencar, M. H., José, R., Ferreira, P., Teixeira, A., Thalles, A.-F., & Garcez, V. (2015). *International Series in Operations Research & Management Science Multicriteria and Multiobjective Models for Risk, Reliability and Maintenance Decision Analysis*. www.springer.com/series/

Forsman, L., & Jonsson, S. (2016). Addressing social sustainability in residential development - An analysis of a residential developer and two municipalities in Sweden. *ROYAL INSTITUTE OF TECHNOLOGY*.

Gurmu, A., Shooshtarian, S., Mahmood, M. N., Hosseini, M. R., Shreshta, A., & Martek, I. (2022). The state of play regarding the social sustainability of the construction industry: a systematic review. *Journal of Housing and the Built Environment*, *37*(2), 595–624. https://doi.org/10.1007/s10901-022-09941-5

Hendiani, S., & Bagherpour, M. (2019). Developing an integrated index to assess social sustainability in construction industry using fuzzy logic. *Journal of Cleaner Production*, *230*, 647–662. https://doi.org/10.1016/j.jclepro.2019.05.055

Karji, A., Woldesenbet, A., Khanzadi, M., & Tafazzoli, M. (2019). Assessment of Social Sustainability Indicators in Mass Housing Construction: A Case Study of Mehr Housing Project. *Sustainable Cities and Society*, *50*. https://doi.org/10.1016/j.scs.2019.101697

Martínez-Blanco, J., Lehmann, A., Muñoz, P., Antón, A., Traverso, M., Rieradevall, J., & Finkbeiner, M. (2014). Application challenges for the social Life Cycle Assessment of fertilizers within life cycle sustainability assessment. *Journal of Cleaner Production*, *69*, 34–48. https://doi.org/10.1016/j.jclepro.2014.01.044

Marzouk, M., & Sabbah, M. (2021). AHP-TOPSIS social sustainability approach for selecting supplier in construction supply chain. *Cleaner Environmental Systems*, *2*. https://doi.org/10.1016/j.cesys.2021.100034

McKenzie, S. (2004). *Social Sustainability: Towards Some Definitions*. http://www.hawkecentre.unisa.edu.au/institute/

Moher, D., Shamseer, L., Clarke, M., Ghersi, D., Liberati, A., Petticrew, M., Shekelle, P., Stewart, L. A., Estarli, M., Barrera, E. S. A., Martínez-Rodríguez, R., Baladia, E., Agüero, S. D., Camacho, S., Buhring, K., Herrero-López, A., Gil-González, D. M., Altman, D. G., Booth, A., … Whitlock, E. (2016). Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015 statement. *Revista Espanola de Nutricion Humana y Dietetica*, *20*(2), 148–160. https://doi.org/10.1186/2046-4053-4-1

Montalbán-Domingo, L., Aguilar-Morocho, M., García-Segura, T., & Pellicer, E. (2020). Study of social and environmental needs for the selection of sustainable criteria in the procurement of public works. *Sustainability (Switzerland)*, *12*(18). https://doi.org/10.3390/SU12187756

Mulliner, E., Smallbone, K., & Maliene, V. (2013). An assessment of sustainable housing affordability using a multiple criteria decision making method. *Omega (United Kingdom)*, *41*(2), 270–279. https://doi.org/10.1016/j.omega.2012.05.002

Nasirzadeh, F., Ghayoumian, M., Khanzadi, M., & Cherati, M. R. (2020). Modelling the social dimension of sustainable development using fuzzy cognitive maps. *International Journal of Construction Management*, *20*(3), 223–236. https://doi.org/10.1080/15623599.2018.1484847

Olukoya, O. A. P., & Atanda, J. O. (2020). Assessing the social sustainability indicators in vernacular architecture—application of a green building assessment approach. *Environments - MDPI*, *7*(9), 1–24. https://doi.org/10.3390/environments7090067

ONU. (1987). Brutland Report: Our Common Future. *World Commission on Environment and Development*.

Petrudi, S. H. H., Ahmadi, H. B., Rehman, A., & Liou, J. J. H. (2021). Assessing suppliers considering social sustainability innovation factors during COVID-19 disaster. *Sustainable Production and Consumption*, *27*, 1869–1881. https://doi.org/10.1016/j.spc.2021.04.026

Roselli, L. R. P., & de Almeida, A. T. (2021). The use of the success-based decision rule to support the holistic evaluation process in FITradeoff. *International Transactions in Operational Research*. https://doi.org/10.1111/itor.12958

Rostamnezhad, M., & Thaheem, M. J. (2022). Social Sustainability in Construction Projects - A Systematic Review of Assessment Indicators and Taxonomy. In *Sustainability (Switzerland)* (Vol. 14, Issue 9). MDPI. https://doi.org/10.3390/su14095279

Shirazi, M. R., & Keivani, R. (2019). The triad of social sustainability: Defining and measuring social sustainability of urban neighbourhoods. *Urban Research and Practice*, *12*(4), 448–471. https://doi.org/10.1080/17535069.2018.1469039

Sierra, L. A., Yepes, V., García-Segura, T., & Pellicer, E. (2018). Bayesian network method for decision-making about the social sustainability of infrastructure projects. *Journal of Cleaner Production*, *176*, 521–534. https://doi.org/10.1016/j.jclepro.2017.12.140

Sierra, L. A., Yepes, V., & Pellicer, E. (2018). A review of multicriteria assessment of the social sustainability of infrastructures. In *Journal of Cleaner Production* (Vol. 187, pp. 496–513). Elsevier Ltd. https://doi.org/10.1016/j.jclepro.2018.03.022

Stewart, T. J. (1992). A Critical Survey on the Status of Multiple Criteria Decision Making Theory and Practice. In *OMEGA Int. J. of Mgrnt Sci* (Vol. 20, Issue 6).

Tranfield, D., Denyer, D., & Smart, P. (2003). Towards a Methodology for Developing Evidence-Informed Management Knowledge by Means of Systematic Review. In *British Journal of Management* (Vol. 14, Issue 3, pp. 207–222). https://doi.org/10.1111/1467-8551.00375

United Nations Department of Economic, U., Affairs Economic Analysis, S., & Division, P. (2022). *World Economic Situation and Prospects 2022*.

Valdes-Vasquez, R., & Klotz, L. E. (2013). Social Sustainability Considerations during Planning and Design: Framework of Processes for Construction Projects. *Journal of Construction Engineering and Management*, *139*(1), 80–89. https://doi.org/10.1061/(asce)co.1943-7862.0000566

Vallance, S., Perkins, H. C., & Dixon, J. E. (2011). What is social sustainability? A clarification of concepts. *Geoforum*, *42*(3), 342–348. https://doi.org/10.1016/j.geoforum.2011.01.002

VillarinhoRosa, L., & Haddad, A. N. (2013). Building Sustainability Assessment throughout Multicriteria Decision Making. *Journal of Construction Engineering*, *2013*, 1–9. https://doi.org/10.1155/2013/578671

Xiao, Y., & Watson, M. (2019). Guidance on Conducting a Systematic Literature Review. In *Journal of Planning Education and Research* (Vol. 39, Issue 1, pp. 93–112). SAGE Publications Inc. https://doi.org/10.1177/0739456X17723971

Zarghami, E., Fatourehchi, D., & Karamloo, M. (2019). Establishing a region-based rating system for multi-family residential buildings in Iran: A holistic approach to sustainability. *Sustainable Cities and Society*, *50*. https://doi.org/10.1016/j.scs.2019.101631

Extending the Value of Predictive Analysis for Demand Forecast and Scheduling Reconsideration

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The COVID-19 pandemic has put a lot of pressure on the healthcare and construction industries. The high transmission rate of virus variants and the low rate of return to work after patients recovered from the disease are the main reasons for this situation. This research focuses on the influences of construction project management challenges on scheduling considerations. After the literature review, this paper compares three event-study methods to establish a methodology for both a regional and a national project demand forecast. Then, this paper explains the process of data collection on economic impacts on labor-intensive markets like construction and demand forecast. In this research, the available datasets were extracted and analyzed from the Department of Health and Human Services and the National Healthcare Safety Network. The analysis indicates that around 20-60% of the population in the U.S. was influenced by the pandemic on the national level. About 30% of the population was affected in the selected state. Using case studies, expert knowledge, and statistical simulations, the data analysis identified causes of resource shortages and substances of scheduling reconsideration. The results indicate that project managers should carefully assess the changed resource limitations that call for flexible and resilient scheduling approaches.

Key Words: Project Capacity Analysis, Value Prediction, Project Management, Scheduling

Introduction

The COVID-19 pandemic, also known as the coronavirus pandemic, is an ongoing global pandemic of coronavirus disease 2019 (COVID-19) caused by the severe acute respiratory syndrome-coronavirus-2. On November 1, 2020, Coronavirus Disease Dashboard Global data, there had been 45,942,902 confirmed cases of COVID-19, including 1,192,644 deaths reported in 219 countries and territories, and more than 18.5 million people recovered (WHO). Moreover, from January 3 to November 1, 2020, there were 8,952,086 confirmed cases of COVID-19 with 228,185 deaths in the U.S. Globally, the United Nations faced a global health crisis unlike any in its 75-year history. The New York Times (DePillis, 2022) reported on Sept. 12, 2022, that the COVID pandemic had caused a loss of at least 500,000 people in the U.S. labor market. The high transmission rate of virus variants and the low rate of return to work after patients recovered from the disease are the main reasons for this situation. Experts predict that if the infection rate in the U.S. cannot be effectively contained, the labor gap may exist for a long time. In early 2022, global economic conditions were weaker than expected (IMF, 2022). Countries have reintroduced measures to limit the movements of people as new Omicron mutants continue to spread. Inflation has risen more than expected, particularly in the U.S. and many emerging markets and developing economies, driven by higher energy prices and supply disruptions. In many labor-intensive markets like construction and hospitality, they used to absorb large numbers of youth employment. Currently, many young people have been laid off or unemployed after graduation, unable to find decent jobs. Since the shortage of skilled construction laborers has been considered a serious issue (Kim et al., 2020), the relevant consideration needs to be thoroughly sorted out.

In the construction industry, such a labor shortage even causes project delivery delays and cost increases. The influences of the pandemic in the U.S. on the labor market are obvious. One million Americans died, unfortunately, and 260,000 of them did not reach their retirement age (DePillis, 2022). Not only that, millions of Americans are retiring early or forced to leave their jobs to care for their families and children. Today, although companies have gradually resumed production and operations, the data shows that the overall willingness of Americans to work is still not as good as before the epidemic (DePillis, 2022). Americans already employed or were looking for a job accounted for 62.4% of the population in August, 1% lower than before the outbreak. Edelberg, director of the Center for Economic Policy at the Brookings Institution, explained that the demand is higher than the supply in the current labor. Therefore, project managers and schedulers should thoughtfully examine resource limitations like skilled labor shortages.

Current scheduling practices often consider weather impacts regarding durations and costs (Marzoughi et al. 2018). Yet, with the skilled labor shortages and unexpected sickness leaves, more practical deliberation should be given to the analysis and predictions of labor shortages and duration extensions. The paper first compares three commonly used event-study methods of a mean-adjusted model, market-adjusted returns model, and risk-adjusted returns model for data analysis. Then the paper discusses the predicted labor demand and calculates the statistics of labor shortages. The following sections show how the construction industry is striving and adjust project schedules to accommodate labor shortages during COVID-19 and how the shortage of capacity can be overcome.

Background

The huge associated number of cases of COVID-19 leads to increasing pressure on hospitals, particularly ICUs, around the globe. The acute shortages of ICU beds, facilities, and staff raise multiple ethical dilemmas related to how to efficiently share the limited available resources to ensure the best possible outcomes (Hao, 2020). Overwhelmed hospitals had to reject patients because of the shortage of life-saving resources and overworked doctors. In the U.S., 20-60% of the population was affected by the disease (Health Affairs Blog. 2020). Among those who develop symptoms, most (about 80%) recovered from the disease without needing hospital treatment (meaning patients with mild symptoms can be treated at home). About 15% became seriously ill and require oxygen and 5% became critically ill and need intensive care. Lispsitchs et al. (2020) estimated that 98,876,254 individuals would be infected, 20,598,725 individuals would require hospitalization, and 4,430,245 individuals would need ICU-level care based on 40% prevalence throughout the pandemic.

Medical facilities like hospitals became the main source for the majority of infected or symptomatic people to seek treatment. The facilities were usually restricted by their capacities when the number of cases increased (especially those in critical condition). The ability of one facility to recover from the influences caused by disturbances is considered its resilience, which depends on its preparedness. Low resilience affects the sustainability of health services.

Researchers are skeptical about whether the U.S. has enough hospital beds to fight the virus spread. CNBC. (2020, April 30); According to a study by Johns Hopkins University, if the U.S. were hit with moderate to severe pandemic outbreaks like the flu of 1918 (a.k.a., Spanish flu), 1 to 10 million people across the county needed to be hospitalized. The New York Times (2020, March 17). Before the outbreak, the NY state had 53,000 beds in 187 hospitals. But that was not enough because more than 57,000 people have been hospitalized for COVID-19 infections in New York alone as of April 26, 2020. There are two main reasons that the U.S. healthcare system is so ill-equipped to handle a crisis (Baldwin 2020; Flynn 2020). The first reason is that over the past four decades, U.S. hospitals have shed more than half a million beds. Secondly, there is a decades-long trend of hospital mergers and closures that have reduced access to care in communities across the nation. Furthermore, it is critical to flatten the infection curve and mitigate the devastation of the coronavirus pandemic (Medical Express 2020). Blavin (2020) suggested that if the curve was not flattened, hospitals across the country would not have the capacity ‘to deal with the surge in hospitalizations associated with COVID-19'. The New York Times (2020) also indicated that in 40% of markets around the country, hospitals would not be able to make enough room for all the COVID-19 patients even if they could empty their beds of other patients.

Even though the market of healthcare construction projects seems to grow rapidly, the skilled labor shortage that the construction industry is experiencing has been intensified by the pandemic. For example, Bettisworth (2018) noticed that the availability of skilled labor resources had a significant influence on project success, which, however, was often considered as a risk factor, instead of a project execution effort. The data from the California labor market showed that workers 55 and older represented 18% while the workers between the ages of 16-25 counted for 9%. The former is almost twice the number of the latter one. After five years, the age-occupation relationships among four categories of workers on a construction site, including carpenters, cement masons, laborers, and operating engineers may have changed. Nevertheless, operating engineers have the most baby boomers than the other occupation types, and this labor group will retire and exit the labor market in the next five years. Given the current labor market situation, the skilled labor of operating engineers will continue to see a shortage for a decade. It becomes a warning sign to the construction industry when the age distribution among occupation types is imbalanced. The age make-up of laborers in the construction market of California may not represent the situation in the entire country, but operating engineer jobs require more training and experience than the other types. Approximately 70% of laborers were over the age of 36 and 50% of workers were over the age of 46. Since this survey was completed before the pandemic, this alarming tendency may very likely continue or even deteriorate because young people (25 or younger) are entering the workforce at a lower rate while much more old people (55 or older) are retiring.

The following comparison (Table 1) between the event-study methods of a mean-adjusted model, market-adjusted returns model, and risk-adjusted model for data analysis, is to identify event causes. This research analyzes the data collected from different sites and validates the accuracy of the data reported by hospitals and published at the state and national sites. The mean-adjusted model is effective in the analysis of cross-sectional analyses like resource shortage, the discrepancy between the state and national reporting, and the projected demand calculated. Though COVID-19 impacted different countries in diverse ways and to varying degrees, this pandemic has demonstrated that sharing best practices is crucial. For example, Kim et al. (2020) suggested that more effort should be spent on the analysis of the impacts of skilled labor shortage on construction project management. An integrated system dynamics can combine the advantages of statistical analysis and simulation to identify the causes and impacts of such shortages. Yet, they only established simulations for five scenarios, which restrained the implementation of their findings (Kim et al., 2020). Researchers affirmed that the construction industry needs to close the gap in knowledge on scheduling reconsiderations caused by the pandemic. This research proposed to study a practical and predictive analytical method for the influence forecasts of skilled labor shortages. The corresponding research objectives are to help industry practitioners understand the trends and impacts of skilled labor shortages and the causes of such situations and to make recommendations for scheduling reconsideration based on recent best practices.

Table 1

Comparison of event-study methods

Method	Definition	Example
Mean adjusted model (Larsen and Resnick, 1999)	A mean-adjusted model corrects statistical averages that included obvious imbalances because of outliers in the dataset, for instance, by inserting categorical variables that separate the data more precisely.	Health Affairs Blog (2020, March 17) used a middle-level estimate of the COVID-19 infection rate of 40%, assuming lengths of stay based on published studies. The model assumed that 50% of pre-occupied beds could be freed up to care for COVID-19 patients. They found that a hospital's referral region affected inpatient and ICU bed capacity significantly. They also observed large variations in the availability of both regular and ICU beds across communities, for instance, some rural communities have adequate numbers of regular beds but often large shortfalls of ICU beds, whereas many more-populous communities have inadequate numbers of total beds but smaller shortfalls of beds.
Market-adjusted returns (Larsen and Resnick, 1999)	Market-adjust returns models use market values at the time to calculate the coefficient adjustments.	This compartmental model can estimate the daily numbers of hospital bed shortages for patients with mild, severe, and critical COVID-19 situations, taking into account underreport and diagnosis delay. The NCBI (2021) used a mathematical model to simulate the epidemic curves of COVID-19 in 51 cities after the adjustment for temporal variation in reporting rates and estimated the shortage of inpatient and ICU beds. They confirmed that the healthcare system was weakened significantly and delayed the provision of healthcare to patients during the lockdown.
Risk-adjusted model (Konchitchki and O'Leary, 2011)	A risk-adjusted model offsets the risks of an individual event.	The NCBI PMC7685049 (2021) investigated global hospital bed (HB), acute care bed (ACB), and ICU bed capacity and determined any correlation between these hospital resources and COVID-19 mortality using a risk-adjusted model. This cross-sectional study utilized data from the WHO and other official organizations regarding global HB, ACB, and ICU bed capacity and performed descriptive statistics and linear regressions. They proved that high-income regions had the best resource allocations of HB and ICU beds, whereas upper-middle-income regions had the highest mean number of ACBs. A weakly positive significant association was

discovered between the number of ICU beds and COVID-19 mortality. No significant associations exist between the number of HBs or ACBs and COVID-19 mortality.

Methodology

The research assumes that real-world data is useful to gather evidence on utilization, population health, and the impact of interventions during COVID-19. The data is collected from reports about U.S. acute care hospitals, critical access hospitals, inpatient rehabilitation facilities, inpatient psychiatric facilities, and long-term acute care hospitals. These hospitals report the COVID-19 data to have access to the data analysis tools through the NHSN applications. Facility-level data is shared in public health emergency response activities by CDC's emergency COVID-19 responses. The DHHS requires all hospitals licensed to provide 24-hour care to report certain data necessary to the all-of-America COVID-19 response CDC. This report of Hospital Data Coverage is representative of the prior week from Friday to Thursday and lists the information of each hospital in the state, the percentage of mandatory fields reported, the number of days reported at 100%, whether a hospital is required to report on Wednesdays only, and each required field with the number of days that specific field was reported for the week. For facilities that are only required to report once a week, the overall count of days will state "100%" and individual field counts will show as "7" if reported successfully or "0" otherwise.

Many hospitals were under unprecedented strains of resources, with limited capacity to treat patients. The Food and Drug Administration (FDA) encourages users and facilities who are concerned about the distribution of a medical product, or anticipate a potential or actual shortage, to notify them. Estimates of hospital capacity are available at the national and state levels on the HHS, CDC, and definitive health care has the overall U.S. hospital beds dashboard. The main pandemic data tracking system is run by the HHS and NHSN. Estimated hospital utilization data are available for the U.S. states, and territories. This data is estimated from hospital submissions, either reported through their state or reported through HHS Protect or NHSN COVID-19 Module.

Organizations monitor data on hospitals' utilization and capacity rates to help researchers, healthcare leaders, and the public identify places with low capacity. They also leverage real-world data to design modeling tools that can help hospitals and health systems plan for critical care surges (Health IT Analytics 2020). Publicly available epidemiological data on COVID-19 and clinical outcomes data from multiple hospitals can help to build the interactive data platform and track hospital bed capacity. State-level organizations also utilize real-world data to demonstrate the impact of COVID-19 on certain communities. These are reliable data sources.

The available data sets were extracted from the HHS and the NHSN of the CDC. The following uses Illinois to analyze the available tools and databases for accuracy (Figure 1). This research utilized several monitoring tools, such as ArcGIS Dashboard® (GARMIN 2020), Definitive Healthcare®, and the Illinois department of public health, to validate the data values. The following activities were performed after the data access was granted: (1) Extracting the data from the databases for each state, based on the selected categories, and creating a master data file in excel. (2) Merging the data files through excel based on the selected data elements for the master data file. (3) Cleaning up the data, by removing invalid and duplicate values. (4) Construct the data where needed based on the research hypothesis. (5) Analyzing only Illinois state data along across all the datafiles and monitoring tools for accuracy. (6) Understanding the conditions used for predictions of demand in healthcare.

OBJECT	state_name	last_updat	total_hospital_Capacity	total_inpatient_beds	total_icu_be
31	Illinois	11/29/2020	33005	28209	4796

inpatient_beds_used_estimat	inpatient_beds_used_covid_es	Available Inpatient Bed	icu_beds_used_estimat	Available ICU Be
18761	5895	3553	2393	2403

	state_Code	collection_date	Total Hospital Capactiy	Total Inpatient Beds	Total Adult ICU Beds
1					
130	IL	11/29/2020	32,573	28,948	3,625

npatient Beds Occupied Estimated	Inpatient Beds Occupied by COVID-19 Patients Estimated	Available Inpatient Beds	Adult ICU Beds Occupied Estimated	Available Adult ICU Beds
18,627	5,805	4,516	2,377	1,248

Figure 1. Screen Shot of Data Files

Results

Estimates of hospital capacity are available at the national and state levels. At the same time as the COVID-19 pandemic continues to disrupt the status quo, the industries turn to real-world data to better understand, monitor and prepare for risks. But not all the results published are straight forwards, and there are many internal factors to determine how the published data could affect a project schedule. As each healthcare facility and organization considers different data elements for reporting and calculating, the capacity and utilization of the reports show different values. Such difference is captured in Figure 2 for the state of Illinois, based on the data reported and collected from all the counties by the Illinois Department of Public Health and the Definitive Healthcare COVID-19 Capacity predictor.

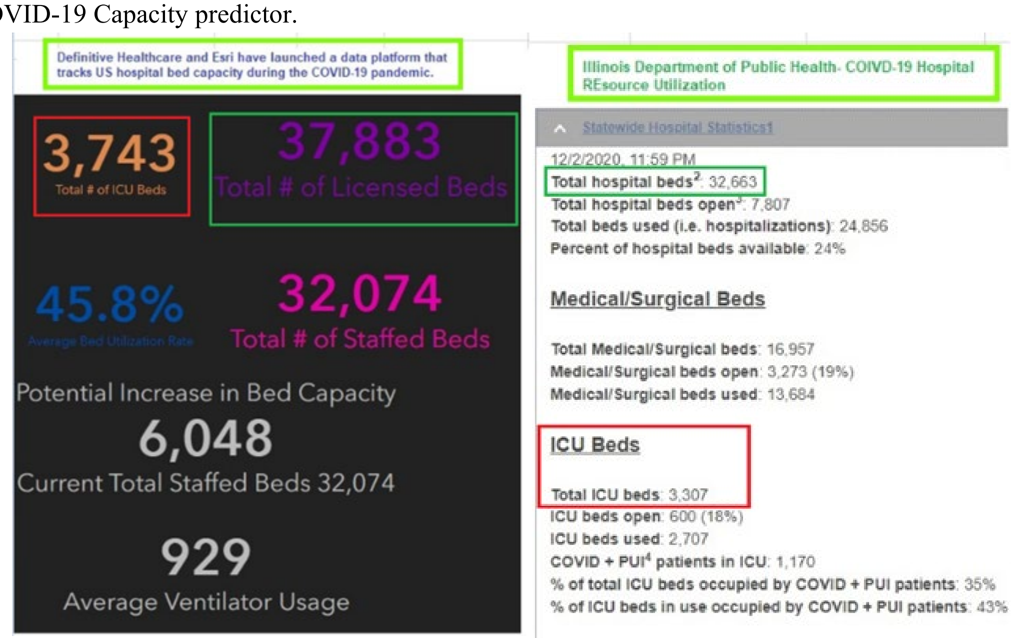

Figure 2. Screen Shot Comparisons from Definitive Healthcare COVID-19 Capacity Prediction and Illinois department of public health COVID-19 Hospital Resource Utilization.

In the U.S., among those who develop symptoms, most (about 80%) recover from the disease without needing hospital treatment, but studies also show that many hospitals across the U.S. regularly operate with most of their beds taken by patients, limiting their ability to handle a sudden increase of COVID-19 patients. As of December 2022, the infectiousness of a COVID-19 patient usually begins to decrease after day 5, but the patient should continue isolation for at least 10 days if in moderate or severe situations (CDC, 2022). A construction schedule should include the possible influences caused by both the continuing skilled labor shortage and the volatile absence caused by the pandemic.

The number of activities and the number of participants in a construction schedule rely on its complexity. Assume a construction project schedule has 100 activities. It includes 20% critical-path activities, which require 80 people as human resources. Using a 95% confidence level, if the same population (approximately 80) were to be sampled on multiple occasions, the estimates of a parameter (in this case, the delay of each critical-path activity) were made on each occasion, this confidence level means that the most-likely average of delay (a.k.a., the true population parameter) falls in the resulting intervals is approximately 95% of the cases. Let n = 40 (50% of 80); x = 7.5 days (based on (CDC, 2022)); s = 2.5 days. The *z* value should be 1.960. The confidence interval of the average delay is calculated using Equation 1. Hence, the CI is $7.5 + 1.960*2.5/\sqrt{40} = 8.275$ days. In the worst-case scenario, the 20 critical-path activities would have 165.5 days of delay. Using the result from Figure 2, 35% - 45.8% of patients could be COVID-positive. Using the mean adjusted model in Table 1, the most likely delay of the project is 165.5 * 0.35 = 58 days.

$$CI = \bar{x} \pm z\frac{s}{\sqrt{n}} \tag{1}$$

Conclusion

The surge in demand for healthcare projects triggered the expected shortage of mechanical systems and other construction materials in the entire market. Construction companies should be ready for the ripple effects of the market caused by the number of infected patients. Project schedules should be adjusted to incorporate the availability uncertainty of skilled construction laborers. This research shows an approach to estimate the most-likely delay of a construction project schedule using publicly available data and a mean adjusted model. More discussions should be encouraged on the project control recommendations amongst team members. This could improve the economic recovery from the pandemic for the country.

This research focuses on the predictive analysis for labor demand forecast and scheduling reconsideration of construction project management. One limit of this research is the data of actual project delay issues because of time duration and scarcity of recorded cases. Future research should consider how to tailor the existing training settings of the construction industry and help reduce structural unemployment.

References

Baldwin, S. (2020, April 30). *Why the US is facing a hospital bed shortage. CNBC.* www.cnbc.com/2020/04/30/how-northwell-health-and-Beaumont-health-make-money.html

CDC. (2022, August 24). What to Do If You Were Exposed to COVID-19. *Centers for Disease Control and Prevention*. https://www.cdc.gov/coronavirus/2019-ncov/your-health/if-you-were-exposed.html

CDC. (2020, March 17). COVID-19 Hospital Data from the National Hospital Care Survey. *Centers for Disease Control and Prevention*. https://data.cdc.gov/NCHS/COVID-19-Hospital-Data-from-the-National-Hospital-/q3t8-zr7t

Centers for Disease Control and Prevention. (2020, July 16). *Current Hospital Capacity Estimates – Snapshot. National Healthcare Safety Network (NHSN)*. https://www.cdc.gov/nhsn/covid19/report-patient-impact.html

Centers for Disease Control and Prevention. (2020, July). *COVID-19 Guidance for Hospital Reporting and FAQs. National Healthcare Safety Network (NHSN)*. https://www.hhs.gov/sites/default/files/covid-19-faqs-hospitals-hospital-laboratory-acute-care-facility-data-reporting.pdf

CNBC. (2020, April 30). *Why the US is facing a hospital bed shortage. CNBC.Com.* www.cnbc.com/2020/04/30/how-northwell-health-and-Beaumont-health-make-money.html

Flynn, A. (2020, April 8). *We're short on hospital beds because Washington let too many hospitals merge.* Washington Post. https://www.washingtonpost.com/outlook/2020/04/08/were-short-hospital-beds-because-washington-let-too-many-hospitals-merge/

GARMIN. (2020, July 13). *Definitive Healthcare: US Hospital Beds Dashboard*. https://www.arcgis.com/apps/opsdashboard/index.html#/8c4dcccd9e3845eb89f6401f919007f2

Hao, K. (2020, April 7). *Here are the states that will have the worst hospital bed shortages. MIT Technology Review*. https://www.technologyreview.com/2020/04/07/998527/coronavirus-us-states-worst-hospital-bed-shortages/

HEALTH AFFAIRS BLOG. (2020, March 17). *American Hospital Capacity and Projected Need for COVID-19 Patient Care*. Healthaffairs.Org. https://www.healthaffairs.org/do/10.1377/hblog20200317.457910/full/

Health IT Analytics. (2020, April 9). *Three Ways the Industry Is Leveraging Real-World Data to Combat COVID-19*. Healthitanalytics. https://healthitanalytics.com/news/3-ways-the-industry-is-leveraging-real-world-data-to-combat-covid-19

Illinois Department of Public Health. (2020, April 10). *Illinois Department of Public Health COVID-19 Statistics* DPH Illinois. https://www.dph.illinois.gov/covid19/covid19-statistics

Kim, S., Chang, S., & Castro-Lacouture, D. (2020). Dynamic modeling for analyzing impacts of skilled labor shortage on construction project management. *Journal of Management in Engineering*, 36(1), 04019035.

Konchitchki, Y., & O'Leary, D. E. (2011). Event study methodologies in information systems research. *International Journal of Accounting Information Systems*, 12(2), 99-115.

Larsen, G. A., & Resnick, B. G. (1999). A performance comparison between cross-sectional stochastic dominance and traditional event study methodologies. *Review of Quantitative Finance and Accounting*, 12(2), 103-113.

Marzoughi, F., Arthanari, T., & Askarany, D. (2018). A decision support framework for estimating project duration under the impact of weather. *Automation in Construction*, 87, 287-296.

Medical Express. (2020, March 26). *U.S. hospital beds were already maxed out before coronavirus pandemic.* Medicalxpress. https://medicalxpress.com/news/2020-03-hospital-beds-maxed-coronavirus-pandemic.html

NCBI PMC7685049. (2021). A Closer Look Into Global Hospital Beds Capacity and Resource Shortages During the COVID-19 Pandemic. Published. doi.org/10.1016/j.jss.2020.11.062

The New York Times. (2020, March 17). *These Places Could Run Out of Hospital Beds as Coronavirus Spreads*. www.nytimes.com/interactive/2020/03/17/upshot/hospital-bed-shortages-coronavirus.html

World Health Organization. (2020, November 1). *WHO Coronavirus (COVID-19) Dashboard. With Vaccination Data*. https://covid19.who.int/

WHO Coronavirus Disease (COVID-19) Dashboard. *(2020, September 12). Who Health Organization.* https://covid19.who.int/region/amro/country/us

Multi-Objective Maintenance Optimization Model to Minimize Maintenance Costs While Maximizing Performance of Bridges

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Proper maintenance planning for bridges is necessary as it impacts the performance, safety, and maintenance costs. Implementing less costly interventions on time can reduce the deterioration of components, enhance performance of bridges, and prevent necessity of costly interventions. However, maintenance of bridges is often delayed due to lack of proper planning and limitations of recourses such as funds. This paper presents the development of a multi-objective maintenance optimization model for bridges that can identify optimum trade-offs between two important objectives of minimizing maintenance costs and maximizing performance of bridges. To this end, a multi-objective model is developed in three main steps: (i) formulation step where decision variables, objective function, and constraints are identified and formulated; (ii) implementation step that performs the model computations; and (iii) performance evaluation step where a case study is analyzed to illustrate the capabilities of the developed model. The computations of the optimization model are implemented using epsilon-constraint method and binary linear programing due to their capability of identifying optimal solutions in a short computational time. The case study results illustrated that the developed model identified pareto-optimal solutions of the above optimization objectives for a study period of 50 years.

Key Words: Multi-objective optimization, Bridge Performance, Bridge Condition, Bridge Maintenance Optimization, Bridge Maintenance Costs

Introduction and the Need

Proper maintenance planning for bridges is necessary as it impacts the performance, safety, and maintenance costs. Implementing less costly interventions on time can reduce the deterioration of components, enhance performance of bridges, and prevent necessity of costly interventions. However, maintenance of bridges is often delayed due to lack of proper planning and limitations of recourses such as funds. To address this problem, a number of studies presented budgeting methods for bridge maintenance prioritization to support decision makers in planning and prioritizing maintenance and renovation activities. For example, Zhang et al. presented a bridge network model to prioritize maintenance interventions for a network of bridges while considering budget constraints. They presented two performance indexes: (1) static priority index (SPI) that measures the performance of networks based on travel time between all possible origin-destination points in networks, and (2) dynamic priority index (DPI) that measures the performance of networks while considering uncertainties governing the performance of the transportation network. The results of the case study showed that the DPI is a more effective ranking mechanism compared to SPI (Zhang and Wang 2017). Similarly, Contreras-Nieto et al. presented a Multi-criteria Decision Making Model (MCDM) for prioritizing bridge maintenance activities and budget allocation. They applied Analytic Hierarchy Process (AHP) to rank the maintenance activities based on bridge experts' opinion on relative importance of maintenance interventions on deck, substructure, superstructure, and scour with respect to bridge resiliency, riding comfort, safety, and serviceability. The results of the case study showed that bridge decks are the most critical component while considering safety, serviceability, and comfort. Moreover, substructure have the highest importance while considering the resiliency criterion (Contreras-Nieto et al. 2019). Using technique for order of preference by similarity to ideal solution (TOPSIS), Das et al. presented a MCDM for prioritizing bridge maintenance interventions based on criteria such as bridge condition index, delay cost, and accessibility. The results of the case study showed that failure of higher priority bridges can lead to higher social costs (Das and Nakano 2021). Other studies considered maintenance and social costs along with the environmental impacts to bridge prioritize maintenance interventions. For example, Gokasar et al. presented a hybrid MCDM to rank bridge maintenance projects while considering various criteria, including cost effectiveness, physical condition, social impact for travelers, and CO_2 emissions. To this end, they integrated fuzzy weighted aggregated sum product assessment and TOPSIS to prioritize bridges maintenance projects. The results of the case study showed that environmental impacts of bridge maintenance projects can dominate the ranking of the maintenance alternatives (Gokasar, Deveci, and Kalan 2022). Despite the contributions of these studies in presenting models for maintenance prioritization, they focus on the short term bridge maintenance and are not capable of generating long term maintenance plans to maximize the performance of bridges within available budgets.

A number of studies focused on developing maintenance optimization models to identify optimal maintenance interventions for bridges to minimize life-cycle-costs (Jaafaru and Agbelie 2022; Nili, Taghaddos, and Zahraie 2021). For example, Ghodoosi et al. presented an optimization model to minimize life cycle costs of bridge structures. The presented model integrated databases of asset inventory, maintenance actions list, reliability–based deterioration model, an intervention effect model, and an optimization model using genetic algorithms to identify optimal intervention scenarios. They applied the model on a simply supported bridge superstructure. The case study showed that undertaking less costly minor repair actions results in 4.5 times more cost saving compared to conventional scenario where only major repairs are performed (Ghodoosi et al. 2018). In a similar study, Abdelkader et al. presented a multi-objective differential evolution optimization model to minimize maintenance time, cost, and greenhouse gases. They applied a discrete event simulation model to simulate the bridge deck replacement process and used a neural-network model to predict time, cost, greenhouse gases, and resource utilization of different intervention plans. The results of the case study showed up to 71%, 28%, and 39% reduction in time, cost, and greenhouse gases compared to conventional methods, respectively (Abdelkader et al. 2021). Nili et al. presented a simulation-based bridge maintenance optimization model that can identify optimum maintenance intervention plans to minimize agency and user costs in bridge repair projects while considering workspace limitations and predecessor relationships. They applied a discrete event simulation to identify optimum sequence of repair-activities for each repair intervention. The result of the case study showed 11% and 4% reduction in user costs and crew cost compared to conventional methods, respectively (Nili et al. 2021). Other studies in the literature showed that implementation of preventive maintenance (PM) reduces the frequency of major maintenance interventions and results in significant reduction in maintenance costs as well as environmental impacts. For example, Xie et al. presented a multi-objective optimization model using genetic algorithm to maximize safety and minimize life cycle cost and life cycle environmental impact. The model is designed to identify optimum timing of preventive maintenance interventions for existing bridges. The result of the case study revealed up to 25% reduction in life cycle environmental impacts compared to conventional methods (Xie, Wu, and Wang 2018). Although the aforementioned studies presented significant contributions to existing knowledge in identifying optimal maintenance interventions, the generated results are constrained by solution quality and/or computational efforts. Specifically, there is limited or no reported studies that focused on identifying optimum trade-offs between minimizing maintenance costs and maximizing performance of bridges.

Research Objectives and Methodology

The present study focuses on developing a new bridge maintenance optimization model that is capable of identifying optimal trade-offs between two primary objectives: (1) minimizing maintenance costs and (2) maximizing performance of bridges. The present model is designed to evaluate cost effectiveness of various maintenance interventions based on maintenance costs, performance index, and specified interest rate. To this end, present value method is used to analyze the maintenance costs over a period of study with respect to a specified interest rate. The present model is expected to support bridge operators in identifying an optimal schedule of maintenance interventions based on available budgets. Epsilon-constraint method and binary linear programing are used to perform the model computations due to their capability of identifying optimal solution in short computational time. The model is developed in three main steps: (i) formulation step where decision variables, objective function, and constraints are identified and formulated; (ii) implementation step that performs the model computations; and (iii) performance evaluation step where a case study is analyzed to illustrate the capabilities of the developed model. The following section describes these steps in details.

Model Development

The decision variables of the optimization model are designed to represent all feasible alternative plans for maintenance of bridge components for a predefined period of study. To linearize the problem and before performing the optimization computations, the model generates all feasible maintenance plans for each of bridge components. Each alternative plan specifies each intervention that should take place in each year. These alternative plans cover all the feasible maintenance plans for bridge components including deck, girder/beam, columns, abutment, pier caps, expansion joints, bridge rail, and steel protective coatings. These maintenance plan alternatives are modeled using "$M_{c,p}$" which is a binary decision variable that represents the selection of maintenance plan number "p" for component "c" from a set of feasible alternatives.

The objective functions of the developed optimization model are designed to generate optimal trade-offs among two optimization objectives: (1) minimizing maintenance costs, and (2) maximizing the performance index of bridges. Bridge maintenance cost can be calculated by adding up maintenance costs during a predefined study period for bridge components including deck, girder/beam, columns, abutment, pier caps, expansion joints, bridge rail, and steel protective coatings, as shown in Equation (1). Similarly, bridge performance can be calculated by weighted average of performance index of the above components during the predefined study period, as shown in Equation (2). Performance indexes of components in each year are calculated using Weibull probability method, as shown in Equation (3). Weibull probability method is widely used in the literature to model deterioration of buildings and infrastructure systems (Ghafoori and Abdallah 2022c, 2022b, 2022a; Toasa Caiza et al. 2020). Moreover, for each bridge in National Bridge Inventory (NBI), National Bridge Elements (NBE) contains data on bridge elements, their quantity, and percentage of each element quantity that are in good, fair, poor, and severe conditions (FHWA 2022). Based on the quantity of each element and cost references such as RSMeans (RSMeans 2020), cost of elements replacement can be calculated. Elements' maintenance cost is estimated based on the cost of elements' replacement, and improvements in condition of elements due to maintenance interventions (Grussing and Marrano 2007), as shown in Equation (4).

$$TBMC = \sum_{c=1}^{C}\sum_{p=1}^{P_C}\sum_{y=1}^{Y} M_{c,p} \times MC_{c,p,y} \tag{1}$$

Where: "$TBMC$" is total bridge maintenance cost; "C" is number of the bridge components; "P_C" is total number of alternative maintenance plans for component "c"; "Y" is number of years in study period; "$MC_{c,p,y}$" is maintenance cost of alternative plan "p", in year "y".

$$BPI = \frac{\sum_{c=1}^{C}\sum_{p=1}^{P_C}\sum_{y=1}^{Y} M_{c,p} \times CPI_{c,p,y} \times W_c}{\sum_{c=1}^{C}\sum_{y=1}^{Y} W_c} \tag{2}$$

Where: "BPI" is bridge performance index; "$CPI_{c,p,y}$" is performance index of component "c" in alternative plan "p", in year "y". "W_c" is user specified weight for component "c".

$$CPI_{c,p,y} = IP_c \times \left(\frac{100}{MP_c}\right)^{-\left(\frac{y}{\beta_c}\right)^{\alpha_c}} + ME_{c,p,y} \tag{3}$$

Where: $CPI_{c,p,y}$ is performance index of component "c" in alternative plan "p" in year "y"; IP_c is initial performance index of component "c"; MP_c is minimum acceptable performance index for component "c"; β_c and α_c are Weibull deterioration function parameters for deterioration of component "c" which depend on operational and environmental condition of components and are determined based on previous data and expert's opinion; and $ME_{c,p,y}$ is improvement in performance index due to maintenance intervention in alternative plan "p" for component "c" in year "y".

$$MC_{c,p,y} = RC_c \times \left(\frac{100 - CPI_{c,p,y}}{100 - MP_c}\right) \tag{4}$$

Where: $MC_{c,p,y}$ is the estimated maintenance cost for component "c" in alternative plan "p" in year "y", and RC_c is cost of replacement of component c.

To ensure that the developed model provides feasible and practical solutions, the optimization model integrates two types of constraints: (i) maintenance plan alternative selection, and (ii) minimum performance indexes for each of components. The maintenance plan alternative selection constraints are integrated in the model due to the use of linear programming to limit the optimization model to select only one plan from the set of feasible plans, as shown in Equation (5). Moreover, the minimum performance indexes constraints are integrated in the model to ensure that maintenance intervention are performed on bridge components before their performance index fall blew the specified limit.

$$\sum_{p=1}^{P_c} M_{c,p} = 1 \qquad \forall\, c = 1, \dots, C \tag{5}$$

Where: "P_C" is total number of alternative maintenance plans for component "c"; and "c" ranges from one to total number of components "C".

Input data of the developed model is fed through a spreadsheet that includes data on: (i) bridge general information such as specifications of deck, girder/beams, columns, abutment, pier caps, expansion joints, bridge rail, and steel protective coatings; (ii) maintenance data such as possible intervention for each of the components; (iii) maintenance cost data for each of components estimated based on NBI and NBE; (iv) performance index data including existing performance, minimum acceptable performance index, and Weibull deterioration parameters for each of components.

The optimization model is implemented in MATLAB environment where it can read bridge data from spreadsheet to identify existing components. Next, based on the existing performance indexes of bridge components, the model generates a set of maintenance plans for each bridge component. Next, maintenance costs along with performance indexes of plans are calculated and stored in a database to be used during the optimization process.

Epsilon-constraint method (Haimes, Lasdon, and Wismer 1971) is used to perform the model computations due to its capability of (1) identifying pareto-optimal solutions for both convex and non-convex problems, and (2) generating pareto-optimal trade-offs for the two optimization objectives in short computational time (Ehrgott 2005). This method converts one of the objective functions to a constraint that ranges from minimum and maximum values of the converted objective function where the full range is divided into "N" number of intervals. N+1 single objective optimization problems are generated and solved based on different values of the converted objective function to generate Pareto solutions of the two objective functions. Binary linear programing is used to solve the converted single-objective optimization problems since it is capable of identifying global optimal solutions in short computational time.

Case Study

A case study of a concrete bridge is performed to evaluate the performance of the model and demonstrate its capabilities. The case study bridge is located in Larimer County, Colorado, and was constructed in 1966 and has a deck area of 627.2 square feet and Average Daily Traffic (ADT) of 12514 vehicles. This bridge consists of a reinforced concrete deck, prestressed concrete girder, reinforced concrete columns, reinforced concrete abutment, reinforced concrete pier cap, strip seal expansion joint, and reinforced concrete bridge rail. The input data is collected based on NBI and NBE, as shown in Table 1.

The present model is used to identify optimal trade-offs among the two optimization objectives: (1) minimizing total maintenance cost, and (2) maximizing bridge performance. The minimum and maximum value of the first objective function, maintenance costs, were calculated by removing the second objective function and solving two single-objective optimization problems as follows: (1) minimizing total maintenance cost and (2) maximizing total maintenance cost. Next, the first objective function, total maintenance cost, was converted to a constraint that ranged from minimum value of $15,040K to maximum value of $24,660K with epsilon increments of 10K. Accordingly, the multi-objective problem was converted to 963 single-objective optimization problems. For each of these single-objective optimization problems, the model performed the calculations and identified optimal maintenance interventions to maximize the performance index of the bridge. The computations resulted in 963 pareto-optimal solutions with respect to the two objective functions, as shown in Figure 1.

The present model can generate detailed recommendations for maintenance interventions for each of the identified points on the pareto-optimal solutions. For example, the model identified maintenance intervention plan to achieve maximum performance index of 81 within maintenance cost of $19,850K, as shown in Figure 1 and Table 2.

The optimization computations were performed on a personal computer with Intel Core i7-10510U M, CPU 2.3 GHz processor, and 8GB RAM. Based on the specified epsilon increments, 963 single-objective optimization computations were executed averagely in 6 seconds. Moreover, the model performed the total computations to achieve the pareto optimal solutions in 96 minutes.

Table 1

Input data of the case study

Element Group	Element Name	Unit	Total Quantity	Existing Performance Index
Deck	Reinforced Concrete Deck	Square Feet	26,609	99.81
Superstructure	Prestressed Concrete Girder/Beam	Linear Feet	2,255	97.07
Substructure	Reinforced Concrete Column	Count	6	100
Substructure	Reinforced Concrete Abutment	Linear Feet	236	97.2
Substructure	Reinforced Concrete Pier Cap	Linear Feet	112	100
Joint	Strip Seal Expansion Joint	Linear Feet	336	84.29
Bridge Rail	Reinforced Concrete Bridge Rail	Linear Feet	472	100
Wearing Surfaces and Protective Coatings	Steel Protective Coating	Square Feet	160	100

Table 2

Action Report for the maintenance budget of 19,850K

Element Group	Element Name	Interventions			
		Year	Action	Year	Action
Deck	Reinforced Concrete Deck	10	Seal deck overlays	20	Seal deck overlays
Superstructure	Prestressed Concrete Girder/Beam	12	Repair concrete	28	Repair concrete
Substructure	Reinforced Concrete Column	14	Repair concrete	30	Repair concrete
Substructure	Reinforced Concrete Abutment	12	Repair concrete	28	Repair concrete
Substructure	Reinforced Concrete Pier Cap	16	Repair concrete	32	Repair concrete
Joint	Strip Seal Expansion Joint	12	Sealing deck joints	28	Sealing deck joints
Bridge Rail	Reinforced Concrete Bridge Rail	16	Repair concrete	32	Repair concrete
Wearing Surfaces and Protective Coatings	Steel Protective Coating	16	Repair Steel Protective Coating	32	Repair Steel Protective Coating

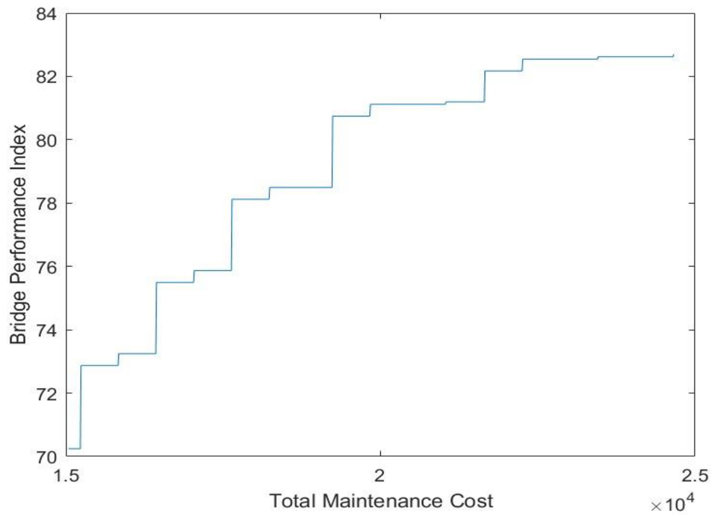

Figure 1. Pareto-optimal solutions for trade-offs among the two optimization objectives

Conclusions and Future Research

This study presented the development of a new model that is capable of identifying optimal trade-offs between two primary objectives of minimizing maintenance costs while maximizing bridge performance. The present model is designed to evaluate cost effectiveness of various maintenance interventions based on maintenance costs, performance index, and specified interest rate. The computations of the optimization model were implemented using epsilon-constraint method and binary linear programing due to their capability of identifying optimal solutions in a short computational time. Based on the epsilon-constraint method, total maintenance cost was converted to a constraint that ranged from the minimum value of $15,040K to the maximum value of $24,660K with epsilon increments of 10K. Accordingly, the multi-objective problem was converted to 963 single-objective optimization problems. For each of these single-objective optimization problems, the model performed the calculations and identified optimal maintenance interventions to maximize the performance index of the bridge. The case study results illustrated that the developed model identified pareto-optimal solutions of the two optimization objectives for a study period of 50 years. The present model can generate detailed recommendations for maintenance interventions for each of the identified points on the pareto-optimal solutions. The optimization model provides new and practical capabilities that enables decision makers to identify an optimal schedule of bridge maintenance interventions based on available annual budgets. It should be noted that the present case study focused on a bridge with reinforced concrete structure in the state of Colorado; and additional research is needed to evaluate other types of structures such as steel structures, and bridges located in other climates. Moreover, the present model applies the Weibull deterioration estimation method, which is subjective, as it relies on expert judgments of deterioration parameters. Therefore, other approaches such as data driven methods can be applied to objectively estimate the deterioration of elements condition. Based on the aforementioned limitations, future research and expansion of the present model include: (1) integrating data driven methods such as machine leaning and deep learning to identify deterioration of bridge components, and (2) evaluating additional case studies of bridges with different structure types and locations.

References

Abdelkader, Eslam Mohammed, Osama Moselhi, Mohamed Marzouk, and Tarek Zayed. 2021. "Integrative Evolutionary-Based Method for Modeling and Optimizing Budget Assignment of Bridge Maintenance Priorities." *Journal of Construction Engineering and Management* 147(9).

Contreras-Nieto, Cristian, Yongwei Shan, Phil Lewis, and Julie Ann Hartell. 2019. "Bridge Maintenance Prioritization Using Analytic Hierarchy Process and Fusion Tables." *Automation in Construction* 101(July 2018):99–110.

Das, Rubel, and Masaaki Nakano. 2021. "A Multi-Criteria Decision-Making Model Using Socio-Technical Attributes for Transportation Bridge Maintenance Prioritisation." *International Journal of Construction Management* 0(0):1–7.

Ehrgott, Mattias. 2005. *Multicriteria Optimization: Second Edition*.

FHWA. 2022. "National Bridge Inventory - Management and Preservation - Bridges & Structures - Federal Highway Administration." Retrieved October 23, 2022 (https://www.fhwa.dot.gov/bridge/mtguide.cfm).

Ghafoori, Mahdi, and Moatassem Abdallah. 2022a. "Building Optimization Model for Minimizing Operation and Maintenance Costs." in *Construction Research Congress 2022: Project Management and Delivery, Controls, and Design and Materials - Selected Papers from Construction Research Congress 2022*. Vols. 3–C.

Ghafoori, Mahdi, and Moatassem Abdallah. 2022b. "Innovative Optimization Model for Planning Upgrade and Maintenance Interventions for Buildings." *Journal of Performance of Constructed Facilities* 36(6):04022051.

Ghafoori, Mahdi, and Moatassem Abdallah. 2022c. "Simulation-Based Optimization Model to Minimize Equivalent Annual Cost of Existing Buildings." *Journal of Construction Engineering and Management* 148(2).

Ghodoosi, Farzad, Soliman Abu-Samra, Mehran Zeynalian, and Tarek Zayed. 2018. "Maintenance Cost Optimization for Bridge Structures Using System Reliability Analysis and Genetic Algorithms." *Journal of Construction Engineering and Management* 144(2).

Gokasar, Ilgin, Muhammet Deveci, and Onur Kalan. 2022. "CO2 Emission Based Prioritization of Bridge Maintenance Projects Using Neutrosophic Fuzzy Sets Based Decision Making Approach." *Research in Transportation Economics* 91(January 2021).

Haimes, Yacov Y., Leon S. Lasdon, and David A. Wismer. 1971. "On a Bicriterion Formulation of the Problems of Integrated Identification and System Optimization." *IEEE Transactions on Systems, Man and Cybernetics* SMC-1(3).

Jaafaru, Hussaini, and Bismark Agbelie. 2022. "Bridge Maintenance Planning Framework Using Machine Learning, Multi-Attribute Utility Theory and Evolutionary Optimization Models." *Automation in Construction* 141:104460.

Nili, Mohammad Hosein, Hosein Taghaddos, and Banafsheh Zahraie. 2021. "Integrating Discrete Event Simulation and Genetic Algorithm Optimization for Bridge Maintenance Planning." *Automation in Construction* 122(February 2020):103513.

RSMeans. 2020. "RS Means Online Database."

Toasa Caiza, Paul Dario, Thomas Ummenhofer, José A. F. O. Correia, and Abilio De Jesus. 2020. "Applying the Weibull and Stüssi Methods That Derive Reliable Wöhler Curves to Historical German Bridges." *Practice Periodical on Structural Design and Construction* 25(4).

Xie, Hui Bing, Wen Jie Wu, and Yuan Feng Wang. 2018. "Life-Time Reliability Based Optimization of Bridge Maintenance Strategy Considering LCA and LCC." *Journal of Cleaner Production* 176:36–45.

Zhang, Weili, and Naiyu Wang. 2017. "Bridge Network Maintenance Prioritization under Budget Constraint." *Structural Safety* 67:96–104.

Wildfire Smoke Exposure and Health Impacts for Outdoor Building Construction Workers in California

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Exposure to wildfire-related smoke has serious implications for the health outcomes of outdoor occupational workers. As wildfire season is becoming more prolonged in California, outdoor building construction workers are at great risk of exposure to particulate matter ($PM_{2.5}$) pollution caused by wildfire smoke. Wildfire smoke $PM_{2.5}$ exposure has been shown to result in short-term health impairments, missed workdays, and long-term disease progression. Studies highlighting the exposure of outdoor building construction workers to wildfire-related $PM_{2.5}$ is limited in the existing literature. Using historical wildfires data, employment data of outdoor building construction workers, and air quality data for $PM_{2.5}$ pollution from 2010-2020, this paper investigates the potential exposure of outdoor building construction workers to wildfire smoke $PM_{2.5}$ in California. Counties which experienced wildfire events were identified by intersecting wildfire perimeters with county boundaries using the geospatial analysis software ArcGIS. Monthly employment during wildfire months and the number of days when the $PM_{2.5}$ air quality reached unhealthy levels during those months were evaluated to find the worker smoke exposure days of each county. Results show that outdoor building construction workers in California are vulnerable to wildfire $PM_{2.5}$ exposure and associated health risks, as the typical wildfire season aligns with peak seasonal construction work.

Key Words: Wildfire, Outdoor worker health, Building construction, California

Introduction

Wildfires have been growing in frequency and severity across the Western U.S. over the past two decades. California has been particularly hard hit by recent wildfires, with longer fire seasons engulfing more acres and affecting larger geographical territories within the state annually (S. Li & Banerjee, 2021). For example, in 2021 over 10,000 wildfires burned approximately 2 million acres of land in California and over half of the top 20 largest wildfires in California history occurred in the past decade (CALFIRE, 2022). Wildfires also pose a public health risk due to poor air quality generated by wildfire smoke, especially for people working outdoors (Liu et al., 2021). Wildfire smoke contains multiple hazardous elements such as gaseous pollutants (e.g., carbon monoxide and nitrogen dioxide), hazardous air pollutants (HAPs) (e.g., polycyclic aromatic hydrocarbons), particulate matter (PM), and other volatile compounds (U.S. Environmental Protection Agency, 2021). In the U.S., wildfires serve as a major source of $PM_{2.5}$ particles (O'Dell et al., 2019), which are fine particulate matter less than 2.5 micrometers in diameter suspended in the air. Wildfire-related $PM_{2.5}$ is considered a major health risk because of its higher toxicity compared to other hazardous pollutants (Yu et al., 2022) and its ability to deeply penetrate human lung tissue and impair the functionality of vital organ systems (Aguilera et al., 2021; Cleland et al., 2021). Annual wildfire $PM_{2.5}$ emissions have been increasing across California with annual emission levels peaking at over 12.1 $\mu g/m^3$ in 2020 – the highest level recorded in the past decade – and higher than the U.S. average annual emissions (7.6 $\mu g/m^3$) and World Health Organization (WHO) recommendations (5.0 $\mu g/m^3$) (California Air Resources Board, 2021). During a wildfire event outdoor workers involved in emergency work (e.g., emergency responders and cleanup crews) and non-emergency work (e.g., construction, utility, and agricultural occupations) are at high risk of wildfire smoke exposure in the workplace (Center for Disease Control and Prevention, 2021).

Outdoor workers comprise about 30% of the total U.S. construction industry labor force (U.S. Bureau of Labor Statistics, 2017). As of the first quarter of 2022, approximately 265,000 outdoor construction workers were employed in California. According to a recent report by the Legislative Analyst's Office of California (LAO, 2022), outdoor construction workers in California are more likely to get exposed to wildfire $PM_{2.5}$, which is associated with health hazards such as asthma, cardiovascular disease, and cognitive impairment. Due to increasing wildfire events and $PM_{2.5}$ exposure for outdoor workers, the California Division of Occupational Safety and Health (Cal/OSHA) passed regulations in 2019 aimed at protecting workers from wildfire smoke particulates (Cal/OSHA, 2021) and applies to workplaces where the Air Quality Index (AQI) for $PM_{2.5}$ exceeds above 150. While some studies have examined wildfire smoke health risks and exposure levels to certain occupations (e.g., farm workers), there are limited studies documenting the exposure of outdoor building construction workers to wildfires.

Literature Review

Occupational exposure to poor outdoor air quality and human health consequences have been discussed in the existing literature. Outdoor workers exposed to any type of $PM_{2.5}$ are at increased risk for Parkinson's disease (Kirrane et al., 2015), reduced lung function (Sehgal et al., 2015), carcinogenic exposure (P. Li et al., 2019), cardiovascular impairment (Zhang & Routledge, 2020), respiratory health disorders (Sundram et al., 2022), and premature mortality (Cleland et al., 2021). Marlier et al. (2022) also found that repeated $PM_{2.5}$ exposure over time led to increased air quality sensitivity. Across all industries, workers spending a greater length of time outdoors are exposed to significantly higher amounts of $PM_{2.5}$ than indoor workers (Tovalin-Ahumada et al., 2007). Negative health impacts from wildfire smoke are more pronounced in populations living in close proximity to wildfire activity, but the effects can be seen in populations miles away from an active wildfire zone (Matz et al., 2020). Stowell et al. (2019) found significant associations between wildfire smoke and acute respiratory outcomes in Colorado. Liu et al. (2021) correlated increases in mortality with increased $PM_{2.5}$ exposure to wildfire smoke during the 2020 Washington wildfires. Sorensen et al. (2021) studied wildfire-related $PM_{2.5}$ exposures in relation to Intensive Care Unit (ICU) admissions in the U.S. and found that a 10 micrograms per cubic meter increase in daily wildfire $PM_{2.5}$ was associated with an over 2.7% increase in ICU admissions five days later.

Outdoor construction workers currently experience a high risk of wildfire smoke exposure, a vulnerability that is expected to increase in the future as wildfire events increase in frequency and severity across the Western U.S. For example, in a study of worker injury claims in Oregon from 2009 to 2018, Evoy et al., (2022) found that wildfire smoke in Oregon led to increased rates of traumatic injury claims among outdoor workers. Zuidema et al. (2021) studied the exposure of outdoor construction workers to wildfire-related smoke in Washington state and found that increasing patterns of $PM_{2.5}$ during the summer months coincided with the seasonal peak in construction employment during the summer months. Moreover, residential damages resulting from wildfires typically result in heightened demand for construction work (Pradhan & Arneson, 2021) in the aftermath of wildfires. Despite the growing health concern for outdoor construction workers exposed to wildfire smoke, there are limited studies highlighting the exposure and negative health outcomes for particular occupations. Therefore, this study aims to address the following research question: 1) *What are the seasonal exposure trends of outdoor building construction workers to wildfire smoke $PM_{2.5}$ during wildfire events in California?* and 2) *How are the outdoor building construction worker exposure days to wildfire smoke $PM_{2.5}$ spatially distributed across counties in California?*

Research Methods

This study analyzed the seasonal and spatial exposure patterns of outdoor building construction workers to wildfire smoke $PM_{2.5}$ during the months when wildfires hit various counties in California from 2010-2020. The research methods included a multi-step process for: i) collection of wildfire events data, ii) collection of county-level employment data for outdoor building construction workers, iii) collection of $PM_{2.5}$ air quality data, and iv) determining seasonal and spatial $PM_{2.5}$ exposure trends.

Data Collection

Three types of historical data were collected for the state of California from publicly available sources: i) County-level monthly employment for outdoor building construction workers, ii) wildfire perimeters, and iii) daily $PM_{2.5}$ air quality. First, county-level monthly employment data for outdoor building construction workers in California were collected from the Quarterly Census of Employment and Wages conducted by the U.S. Bureau of Labor Statistics (U.S. Bureau of Labor Statistics, 2022). County-level monthly employment data of sector 2381 of the North American Industry Classification System (NAICS) was collected from 2010 to 2020. The NAICS 2381 sector represents the majority of outdoor works involved in building construction and collectively includes trades working in concrete foundation and structure, structural steel and precast concrete, framing, roofing, glass and glazing, masonry, and siding or cladding (Executive Office of the President Office of Management and Budget, 2022). Employment data was limited to 46 of 58 California counties due to availability. Geographic Information System (GIS) data for historical wildfire perimeters was collected from the Fire and Resource Assessment Program (FRAP) under the California Department of Forestry and Fire Protection (CAL FIRE) (FRAP, 2022). The FRAP geodatabase included the timing and geographic location of fire perimeters in California dating back to 1959 and provided information such as the name of the fire, start and contained date, and burned acres. Finally, outdoor air quality data for $PM_{2.5}$ pollutant for the years 2010-2020 was collected from the U.S. Environmental Protection Agency (U.S. Environmental Protection Agency, 2022). The air quality data was collected from all the monitoring sites of the California counties which included daily mean time series of the $PM_{2.5}$ concentration and its corresponding Air Quality Index (AQI). For $PM_{2.5}$ pollutants, an AQI value less than 50 is considered 'good', above 50 to 100 is considered 'moderate', 101 to 150 is 'unhealthy for sensitive groups,' above 150 is 'unhealthy,' and above 300 is defined as 'hazardous' (AirNow, 2022).

Data Analysis

Data analysis included: i) importing historical fire perimeter geodatabase in GIS software, ii) data filtering, and iii) performing exploratory spatial analysis. ArcGIS Pro Version 2.9 software was used for processing geospatial data. County-level exposure to the burned area of each wildfire was identified using the historical wildfire perimeters from the FRAP (Aguilera et al., 2021). Historical fire perimeter geodatabase from the FRAP was imported to ArcGIS software and the wildfire events of Class E and above (i.e., 300 acres or more in total burnt area) were extruded out to include in the analysis. Wildfires with a total burnt area of 300 acres or more are considered large fires (National Interagency Fire Center, 2021) with a higher potential for particle pollution (Jaffe et al., 2008). Since the wildfire perimeters were sometimes spread across the county boundary, the wildfire perimeter polygons were intersected over the county boundary to get the wildfire perimeters within each county.

Seasonal exposure patterns of outdoor building construction workers to wildfire-related $PM_{2.5}$ was determined based on the monthly employment of outdoor building construction workers during wildfire months of affected counties and the air quality index (AQI) for $PM_{2.5}$ during those months from 2010-2020. First, wildfire events occurring from 2010 to 2020 for each study county, date of ignition, and date of containment were recorded. The month/s covering the start date to the wildfire containment date was referred to as the *wildfire month/s* for that county and the county-level employment of building exterior workers during those months was tabulated. Second, the number of days when $PM_{2.5}$ AQI index exceeded 100 was determined for each wildfire month using the AQI data. For any county at the study year *i* and month *j*, the outdoor building construction worker exposure days to wildfire smoke $PM_{2.5}$ for AQI>100 was determined by taking the product of monthly employment at *month(i,j)* and the number of days in that month when the AQI exceeded 100 (Zuidema et al., 2021). Finally, the spatial exposure patterns of outdoor building construction workers to $PM_{2.5}$ for AQI greater than 100 was determined based on the monthly employment of outdoor building construction workers during the wildfire events and AQI for $PM_{2.5}$ during those events. For each county, the annual worker exposure days to wildfire smoke $PM_{2.5}$ was calculated by summing up the worker smoke exposure days for every month from January to December and the spatial distribution of mean worker smoke exposure days for the study period was mapped in GIS.

Results and Discussion

From 2010 to 2020, a total of 773 Class E wildfire incidents (burnt area >300 acres) burned over 10.5 million acres of land which added to the $PM_{2.5}$ concentration loading in California. Figure 1 shows the seasonal distribution of employment of outdoor building construction workers during wildfire events along with the mean monthly incidences of wildfire events in California for the study period (2010-2020). The axis on the left denotes the mean monthly employment for the study period and the axis on the right denotes the mean monthly wildfire incidents from 2010-2020. Employment levels reached their peak in September and then declined during the winter months.

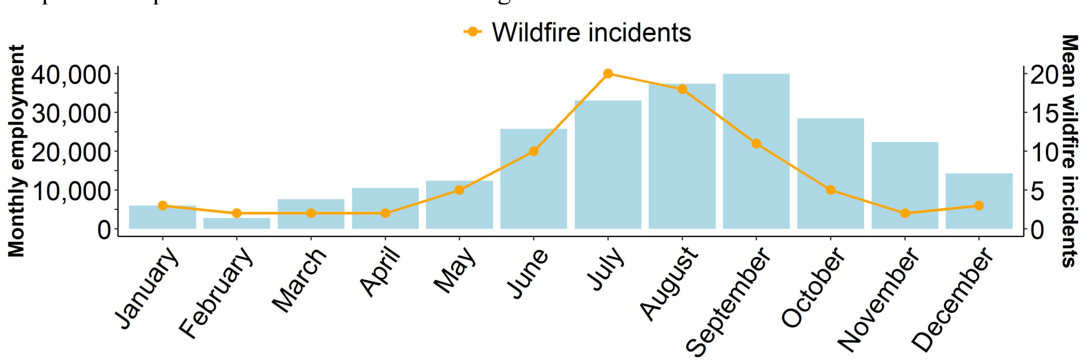

Figure 1. Monthly distribution of employment of outdoor building construction workers and mean monthly wildfire incidences in California during the study period (2010-2020)

Box plots of daily AQI values for $PM_{2.5}$ from January to December recorded by stations across California counties burned by wildfire events from 2010-2020 are shown in Figure 2. $PM_{2.5}$ concentrations reached high values during the months from August to December. This shows that outdoor building construction workers had a greater potential of getting exposed to wildfire smoke $PM_{2.5}$ during those months. The AQI values for $PM_{2.5}$ were relatively high during the month of September when the industry had more outdoor building construction workers gainfully employed.

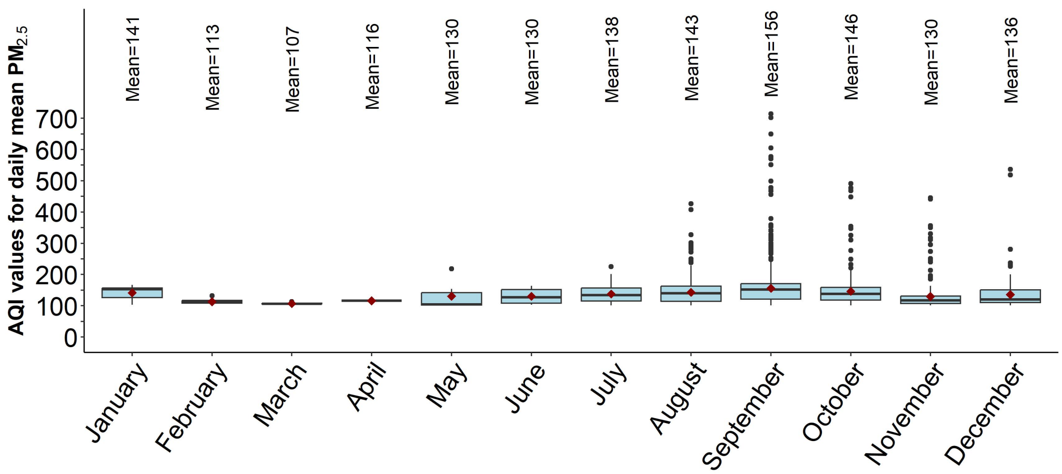

Figure 2. Box plot of AQI values exceeding 100 for daily mean $PM_{2.5}$ (2010-2020)

Figure 3 shows the worker exposure days to wildfire smoke $PM_{2.5}$ during the wildfire seasons which increased starting from July and reached its peak in September. For each month, the total worker smoke exposure days for all the study counties were summed and the mean value of all the wildfire-affected years was plotted. High values of worker smoke exposure days indicated that more workers had the potential of getting exposed to unhealthy air quality and hence more risks of $PM_{2.5}$-related health disorders among outdoor building construction workers.

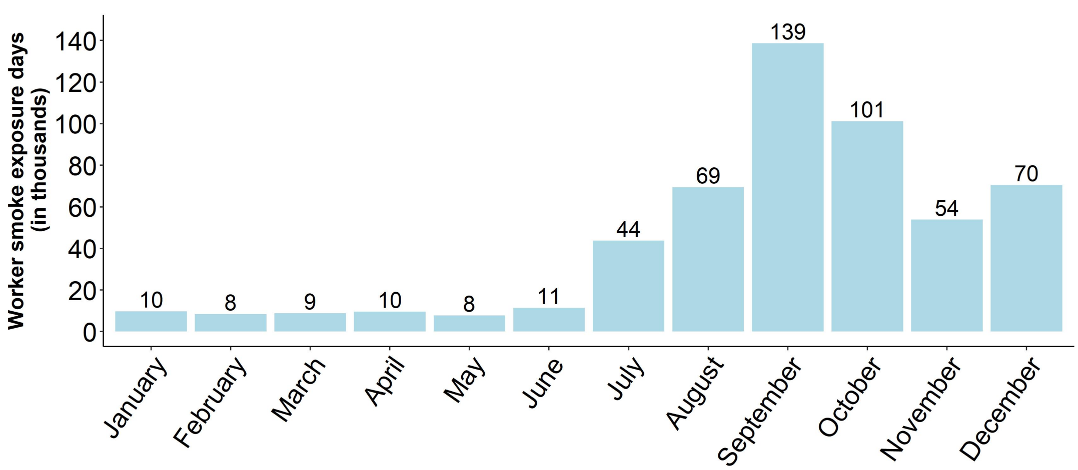

Figure 3. Seasonal distribution of outdoor building construction worker-exposure days to AQI exceeding 100 for $PM_{2.5}$ (2010-2020)

Finally, the spatial distribution of worker smoke exposure days to $PM_{2.5}$ for AQI exceeding 100 during wildfire events was mapped in ArcGIS as shown in Figure 4. For each county, the annual worker smoke exposure days was determined by summing up the monthly worker smoke exposure days and the mean of all the wildfire-affected years in the study period was plotted on the map. The spatial distribution of worker smoke exposure days across California counties showed that counties in Southern California such as Los Angeles, Orange, Riverside, San Bernardino, and San Diego had the highest average worker smoke exposure days during the study period. The monthly employment concentration of outdoor building construction workers in counties like Los Angeles, Orange, and Riverside counties were among the highest in the state. On top of that, counties like Los Angeles, Riverside, and San Bernardino recorded some of the highest numbers of days where AQI for $PM_{2.5}$ exceeded 100 in the past decade. From Northern California, counties such as Santa Clara, Sacramento, Alameda, Fresno, Contra Costa, and Stanislaus had the highest number of worker smoke exposure days. The average monthly number of outdoor building construction workers in those counties were relatively higher than the rest of the counties in Northern California. While counties in Northern California such as Tulare, Butte, Plumas, Madera, and Siskiyou had recorded some of the highest numbers of days when AQI exceeded 100, the worker smoke exposure days were relatively lower because of the lower number of workers employed per month. The total worker smoke exposure days in Southern California counties were found to be higher than those in Northern California which made outdoor building construction workers employed in Southern California counties extremely vulnerable to wildfire smoke exposure.

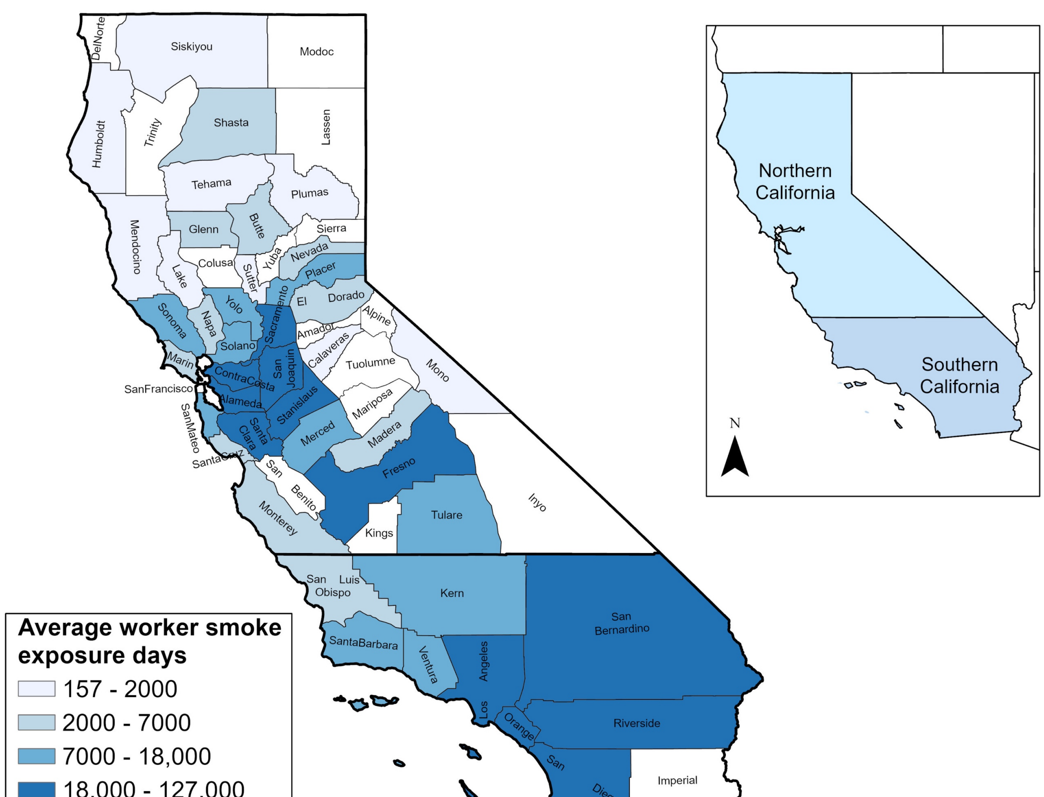

Figure 4. Spatial distribution of average worker smoke exposure days for $PM_{2.5}$ AQI > 100 across counties affected by wildfires in California from 2010-2020

Conclusion

This study reveals new insights about the potential exposure of outdoor building construction workers to wildfire smoke $PM_{2.5}$ in California and its repercussions on the health of workers. Results highlighting the seasonal distribution of employment (Figure 1), variations in air quality during wildfire seasons (Figure 2), seasonal distribution of worker smoke exposure days (Figure 3), and spatial distribution of worker smoke exposure days across California counties (Figure 4) help capture the temporal and spatial trends in outdoor building construction workers' exposure to wildfire smoke $PM_{2.5}$ in California. Historical seasonal patterns of wildfire events show that wildfire season was typically at its peak during the summer months (i.e., June to August) where more incidents of wildfires were recorded during those months. Historical seasonal employment patterns reveal that the summer months had the highest number of outdoor building construction workers in the industry for the entire state of California, coinciding with the period when more wildfire events occurred. Also, the air quality index (AQI) levels for $PM_{2.5}$ during peak wildfire seasons in the summer months were found to be relatively higher. The average monthly building exterior construction workers employed during those summer months was above 25,000, with many workers consistently exposed to dangerous levels of wildfire smoke $PM_{2.5}$. The findings are consistent with the existing literature that outdoor workers are more vulnerable to wildfire smoke exposure during the summer months (Zuidema et al., 2021) because of the seasonal cycles of employment in the construction industry (Geremew & Gourio, 2018). However, the findings added new insights by highlighting how outdoor building construction workers in the counties of Southern California have more potential for wildfire smoke exposure due to higher employment concentration per county and higher AQI levels induced by frequent wildfires. As a result, outdoor building construction workers can be prone to respiratory illness hospitalizations as result of repeated exposure to wildfire smoke (Aguilera et al., 2021).

Outdoor building construction workers in California are more vulnerable to health disorders due to repeated exposure to wildfire smoke induced $PM_{2.5}$ as shown by the results of this study. Cal/OSHA's recent wildfire smoke regulations mandate employers to take special precautions when AQI exceeds 150. Employers are required to provide some N95 respirators that effectively protect the wearers from inhalation of $PM_{2.5}$, reduce work intensity, provide additional rest periods, and relocate work sites. However, these regulations only compel employers to have N95 respirators available – they do not require employees to actually use any protective masks. Additionally, it is not known to what extent employers are following the new mandate. Repeated exposure to wildfire smoke $PM_{2.5}$ can cause several health disorders in outdoor building construction workers. Contractors should ensure they have enough supplies of N95 masks, especially during the summer months when there is a high probability of wildfire incidences. As future wildfires are getting worse in California, more building construction workers are at risk of getting exposed to wildfire smoke-related health disorders. The findings of this study aim to spread awareness about the risks and health issues caused by exposure to wildfire smoke $PM_{2.5}$. As outdoor building construction workers and contractors become more informed of the serious health risks posed by wildfire smoke $PM_{2.5}$, perhaps the construction industry and government agencies will require outdoor workers to use protective masks to prevent the negative health effects of repeated exposure to wildfire smoke.

References

Aguilera, R., Corringham, T., Gershunov, A., & Benmarhnia, T. (2021). Wildfire smoke impacts respiratory health more than fine particles from other sources: Observational evidence from Southern California. *Nature Communications*, *12*(1), 1493. https://doi.org/10.1038/s41467-021-21708-0

AirNow. (2022). *Air Quality Index (AQI) Basics*. https://www.airnow.gov/aqi/aqi-basics/#:~:text=How%20does%20the%20AQI%20work,300%20represents%20hazardous%20air%20quality.
CALFIRE. (2022). *Top 20 Largest California Wildfires*. https://www.fire.ca.gov/media/4jandlhh/top20_acres.pdf
California Air Resources Board. (2021). *Wildfire Emission Estimates for 2021*. https://ww2.arb.ca.gov/sites/default/files/classic/cc/inventory/Wildfire%20Emission%20Estimates%202000-2021.pdf
Cal/OSHA. (2021). *§5141.1 Protection from Wildfire Smoke*. https://www.dir.ca.gov/title8/5141_1.html
Center for Disease Control and Prevention. (2021). *Outdoor Workers Exposed to Wildfire Smoke*. https://www.cdc.gov/niosh/topics/firefighting/wffsmoke.html
Cleland, S. E., Serre, M. L., Rappold, A. G., & West, J. J. (2021). Estimating the Acute Health Impacts of Fire-Originated PM2.5 Exposure During the 2017 California Wildfires: Sensitivity to Choices of Inputs. *GeoHealth*, *5*(7), e2021GH000414. https://doi.org/10.1029/2021GH000414
Evoy, R., Hystad, P., Bae, H., & Kincl, L. (2022). The impact of wildfire smoke and temperature on traumatic worker injury claims, Oregon 2009–2018. *Health Science Reports*, *5*(5), e820. https://doi.org/10.1002/hsr2.820
Executive Office of the President Office of Management and Budget. (2022). *NORTH AMERICAN INDUSTRY CLASSIFICATION SYSTEM*. https://www.census.gov/naics/reference_files_tools/2022_NAICS_Manual.pdf
FRAP. (2022). *Fire perimeters*. https://frap.fire.ca.gov/frap-projects/fire-perimeters/
Geremew, M., & Gourio, F. (2018). Seasonal and business cycles of U.S. employment. *Economic Perspectives*. https://doi.org/10.21033/ep-2018-3
Jaffe, D., Hafner, W., Chand, D., Westerling, A., & Spracklen, D. (2008). Interannual Variations in PM2.5 due to Wildfires in the Western United States. *Environmental Science & Technology*, *42*(8), 2812–2818. https://doi.org/10.1021/es702755v
Kirrane, E. F., Bowman, C., Davis, J. A., Hoppin, J. A., Blair, A., Chen, H., Patel, M. M., Sandler, D. P., Tanner, C. M., Vinikoor-Imler, L., Ward, M. H., Luben, T. J., & Kamel, F. (2015). Associations of Ozone and PM2.5 Concentrations With Parkinson's Disease Among Participants in the Agricultural Health Study. *Journal of Occupational and Environmental Medicine*, *57*(5), 509–517. JSTOR.
LAO. (2022). *Climate Change Impacts Across California—Health*. https://lao.ca.gov/Publications/Detail/4580
Li, P., Yu, J., Bi, C., Yue, J., Li, Q., Wang, L., Liu, J., Xiao, Z., Guo, L., & Huang, B. (2019). Health risk assessment for highway toll station workers exposed to PM2.5-bound heavy metals. *Atmospheric Pollution Research*, *10*(4), 1024–1030. https://doi.org/10.1016/j.apr.2019.01.011
Li, S., & Banerjee, T. (2021). Spatial and temporal pattern of wildfires in California from 2000 to 2019. *Scientific Reports.*, *11*(1).
Liu, Y., Austin, E., Xiang, J., Gould, T., Larson, T., & Seto, E. (2021). Health Impact Assessment of the 2020 Washington State Wildfire Smoke Episode: Excess Health Burden Attributable to Increased PM2.5 Exposures and Potential Exposure Reductions. *GeoHealth*, *5*(5), e2020GH000359. https://doi.org/10.1029/2020GH000359
Marlier, M., Brenner, K., Liu, J., Mickley, L., Raby, S., James, E., Ahmadov, R., & Riden, H. (2022). Exposure of agricultural workers in California to wildfire smoke under past and future climate conditions. *Environmental Research Letters*, *17*, 094045. https://doi.org/10.1088/1748-9326/ac8c58

Matz, C. J., Egyed, M., Xi, G., Racine, J., Pavlovic, R., Rittmaster, R., Henderson, S. B., & Stieb, D. M. (2020). Health impact analysis of PM2.5 from wildfire smoke in Canada (2013–2015, 2017–2018). *Science of The Total Environment*, *725*, 138506. https://doi.org/10.1016/j.scitotenv.2020.138506

National Interagency Fire Center. (2021). *National Report of Wildland Fires and Acres Burned by State*. https://www.nifc.gov/fire-information/statistics

O'Dell, K., Ford, B., Fischer, E. V., & Pierce, J. R. (2019). Contribution of Wildland-Fire Smoke to US PM2.5 and Its Influence on Recent Trends. *Environmental Science & Technology*, *53*(4), 1797–1804. https://doi.org/10.1021/acs.est.8b05430

Pradhan, S., & Arneson, E. (2021). Postdisaster Labor-Demand Surge in the US Highways, Roads, and Bridges Construction Sector. *Journal of Management in Engineering*, *37*(1), 04020102. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000869

Sehgal, M., Suresh, R., Sharma, V. P., & Gautam, S. K. (2015). Assessment of outdoor workers' exposure to air pollution in Delhi (India). *International Journal of Environmental Studies*, *72*(1), 99–116. https://doi.org/10.1080/00207233.2014.965937

Sorensen, C., House, J. A., O'Dell, K., Brey, S. J., Ford, B., Pierce, J. R., Fischer, E. V., Lemery, J., & Crooks, J. L. (2021). Associations Between Wildfire-Related PM2.5 and Intensive Care Unit Admissions in the United States, 2006–2015. *GeoHealth*, *5*(5), e2021GH000385. https://doi.org/10.1029/2021GH000385

Stowell, J. D., Geng, G., Saikawa, E., Chang, H. H., Fu, J., Yang, C.-E., Zhu, Q., Liu, Y., & Strickland, M. J. (2019). Associations of wildfire smoke PM2.5 exposure with cardiorespiratory events in Colorado 2011–2014. *Environment International*, *133*, 105151. https://doi.org/10.1016/j.envint.2019.105151

Sundram, T. K. M., Tan, E. S. S., Cheah, S. C., Lim, H. S., Seghayat, M. S., Bustami, N. A., & Tan, C. K. (2022). Impacts of particulate matter (PM2.5) on the health status of outdoor workers: Observational evidence from Malaysia. *Environmental Science and Pollution Research*, *29*(47), 71064–71074. https://doi.org/10.1007/s11356-022-20955-y

Tovalin-Ahumada, H., Whitehead, L., & Blanco, S. (2007). Personal exposure to PM2.5 and element composition—A comparison between outdoor and indoor workers from two Mexican cities. *Atmospheric Environment*, *41*(35), 7401–7413. https://doi.org/10.1016/j.atmosenv.2007.05.059

U.S. Bureau of Labor Statistics. (2017). *Over 90 percent of protective service and construction and extraction jobs require work outdoors*. https://www.bls.gov/opub/ted/2017/over-90-percent-of-protective-service-and-construction-and-extraction-jobs-require-work-outdoors.htm

U.S. Bureau of Labor Statistics. (2022). *Quarterly Census of Employment and Wages*. Quarterly Census of Employment and Wages

U.S. Environmental Protection Agency. (2021). *Why Wildfire Smoke is a Health Concern*. https://www.epa.gov/wildfire-smoke-course/why-wildfire-smoke-health-concern

U.S. Environmental Protection Agency. (2022). *Outdoor Air Quality Data*. https://www.epa.gov/outdoor-air-quality-data/download-daily-data

Yu, Y., Zou, W. W., Jerrett, M., & Meng, Y.-Y. (2022). Acute Health Impact of Convectional and Wildfire-related PM2.5: A narrative review. *Environmental Advances*, 100179. https://doi.org/10.1016/j.envadv.2022.100179

Zhang, S., & Routledge, M. N. (2020). The contribution of PM2.5 to cardiovascular disease in China. *Environmental Science and Pollution Research*, *27*(30), 37502–37513. https://doi.org/10.1007/s11356-020-09996-3

Zuidema, C., Austin, E., Cohen, M. A., Kasner, E., Liu, L., Busch Isaksen, T., Lin, K.-Y., Spector, J., & Seto, E. (2021). Potential impacts of Washington State's wildfire worker protection rule on construction workers. *Annals of Work Exposures and Health*, *66*(4), 419–432. https://doi.org/10.1093/annweh/wxab11

Materials Delay Impact due to COVID-19 on Construction Projects

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The COVID-19 pandemic has affected all businesses across the globe, particularly, the material supply disruption delaying many construction projects. This material supply disruption presents unprecedented challenges to construction companies in terms of coping with the new circumstances. The purpose of this study is to analyze the materials delivery impact due to the COVID-19 pandemic on construction projects schedule. This study was completed through a quantitative methodology using as a collection instrument an online questionnaire targeting construction company executive members across the United States. The questions and analysis presented in this paper focus on Master Format divisions 40 to 48 of the Construction Specifications Institute corresponding to the projects' process equipment activities. The result shows that the pandemic increased project duration and disrupted the supply chain of the project activities. The findings can provide a better understanding and solution to reduce the impact of supply chain disruptions caused by future pandemics (or wars as the one currently in Ukraine) on the construction industry.

Key Words: COVID-19 Impact, Material Delivery Delay, Construction Cost

Introduction

As of October 2022, according to the CDC's COVID Data Tracker, in the United States (U.S.) alone there have been over 97 million total cases of COVID-19 and over one million deaths attributed to COVID-19 (CDC 2022a). COVID-19 mortality risk has been linked to factors that include older age, male sex, history of diabetes, lymphopenia, and increased procalcitonin (Yu, C., et al., 2020). Unfortunately, Brown et al. (2020) found that nearly 60% of the construction workforce has at least one risk factor (such as: older age, racial and/or ethnic minorities, and smoking and e-cigarette use) that makes them vulnerable to severe illness from COVID-19.

Given the significant impact of COVID-19 in the U.S. and across the globe the ability of factories to produce construction materials and distribute them has suffered a bottleneck. Consequently, the construction industry has been highly impacted by the pandemic due to COVID-19 (Araya, F. 2021). The COVID-19 pandemic has impacted construction projects in many ways (Kisi, K. & Sulbaran, T., 2022). COVID-19 impacted performance, suspension of projects, workforce shortage, and time and cost overruns (Gamil & Alhagar 2020; Shen et al., 2020). Moreover, Bailey et al. (2020) added that construction and engineering projects around the world are being impacted by the COVID-19 pandemic in numerous ways, and many projects had stopped.

It is beneficial for construction professionals to understand how the COVID-19 pandemic has impacted their daily lives and affected their construction schedule so that they are better prepared for future projects during a similar pandemic (or wars as the one currently in Ukraine) that disrupt the production and distribution of construction materials. This study discusses how the COVID-19 pandemic has impacted material supply disruption in the construction industry and how it has affected the construction projects' duration. The study focuses on project delays due to material supply disruption in the Construction Specification Institute (CSI) Master Format process and equipment divisions.

Literature Review

Overview *COVID-19*

The coronavirus disease 2019 also known as COVID-19 is a respiratory illness caused by the virus named severe acute respiratory syndrome coronavirus 2 (i.e., SARS-CoV-2) (CDC 2021; WHO 2021). The Centers for Disease Control and Prevention (CDC) states that the coronavirus is confirmed as being transmitted from human to human and results in symptoms including fever, dry cough, fatigue, and shortness of breath (CDC 2021). Many countries have been experiencing economic slowdowns, financial and labor burdens associated with project delays, cost escalations, lack of supplies, and worker safety and health problems (Al Amri and Marey-Perez, 2020; Denny-Smith et al., 2021; Esa et al., 2020; Kaushal & Najafi, 2021).

COVID-19 transmission is primarily airborne as droplets from person to person such as coughing (Fenelly 2020; CDC 2020). Since the virus can remain in the air and transmit through self-inoculation such as nose and mouth, or by hand contact, the strategy for prevention has been to limit person-to-person contact, either through social distancing or completed reduction in social contact such as lockdowns or shut down of workplaces and public events. The initial guideline from CDC was to wear a mask, maintain at least a 6-foot social distance, cleaning of contact surfaces, and handwash (CDC 2019). Over time the CDC guideline has changed and as Oct 2022 CDC indicates that vaccination is the safest way to help build protection. CDC suggests getting all recommended vaccine doses and boosters as soon as possible to maximize protection and as Oct 2022 72.4% of people five years or older are fully vaccinated in the U.S. (CDC 2022b).

Challenges and Mitigation of Construction Supply Chain Disruption

The construction of projects is considered by many a service industry. However, The U.S. Bureau of Labor Statistics classifies it as a good-producing sector, not a service sector (Valle, G. 2022). As a good-producing sector, COVID-19 had a significant impact on its construction supply change. The COVID-19 pandemic caused supply and demand disruptions with resonating effects (McMaster, M. et al. 2020). Research results unveil that manufacturing firms have faced limited production and delays in procuring goods and services, while distribution centers have been challenged with inventory shortages. Furthermore, supplying firms have encountered increased lead times amid the COVID-19 outbreak (Butt, A. 2022). Studies reveal that the supply chain for construction projects has been significantly affected by COVID-19 (Susanti, R. et al., 2021).

COVID-19 allowed researchers to study supply chain disruptions to gain an understanding of possible approaches to reduce the impact of future pandemics (or wars like the one currently in Ukraine) on the good-producing sector such as the construction industry. The results of some research indicate that strategies such as: “manufacturing flexibility”, “diversifying the source of supply”, and “developing backup suppliers” will have significant positive consequences for managing the impacts in the supply chain of future pandemics (Taqi, H. et al., 2020). Additionally, including flexibility in the management of the supply chain will mitigate the risk of both future epidemics and demand variability (McMaster, M. et al., 2020). It is evident that the mitigation actions proposed such as redundancy and flexibility are good strategies to mitigate supply chain disruptions (due to future events), but there is also a stronger pressure for digitalization and supply-based localization (Pujawan, I. N. & Bah, A. U., 2022). The finds of research of previous papers as well as the ones presented in this paper are important as they help managers recover from supply chain disruptions by identifying and classifying the impacts and strategies required to manage the major supply chain disturbances (Taqi, H. et al., 2020).

COVID-19 Pandemic Impact on Construction Projects

Construction management is a difficult decision-making process including constant time and cost constraints (Okonkwo, C., et al, 2022). Construction was significantly impacted by the COVID-19 pandemic. In the early stage of the COVID-19 pandemic in 2020, a significant number of construction workers reportedly tested positive for COVID-19 (Alsharef et al., 2021; Allan-Blitz et al., 2020). Pasco et al. (2020) emphasized that the risk of COVID-19 infections among construction workers was about five times more likely to be hospitalized because of COVID-19 than workers in other industries. Although an important component of a COVID-19 protection plan is to educate workers with information on the most current science and protective practices to reduce disease spread (Choi & Staley 2021), research shows that levels of workplace safety literacy and risk perception in the construction industry are influenced by factors such as safety training, hazard recognition, risk-taking behaviors, attitudes, and the dynamic nature of the profession (Namian et al., 2016; Gunduz & Ahsan, 2018; Pandit et al., 2019; Loosemore & Malouf, 2019; Uddin et al., 2020). Studies have highlighted varieties of issues in construction such as aging workers and the entrance of “Gen Z” into the workplace, technological modernization, improving efficiency, and the use of sustainability and renewable products (Ayodele et al., 2020; Brown, 2019; Choi et al., 2018; Heigl, 2018; Rodriguez, 2019; Zidan et al., 2013). The COVID-19 crisis led to a reduction in site productivity, increased compliance costs, delayed projects, and increased construction workers' exposure to risk and infections(Olanrewaju, A.L., et al, 2021). A study found the most prominent impacts of COVID-19 were the suspension of projects, labor impact, job loss, time overrun, cost overrun, and financial implications (Gamil, Y., & Alhagar, A., 2020).

Methodology

A quantitative methodology was implemented because the purpose of this study was to generate knowledge and create an understating of a specific subject(Allen, M., 2017). More specifically, this study aimed to understand the impact of the COVID-19 pandemic on construction project delays in the activities in the CSI Master Format divisions 40 to 48 (projects’ process equipment activities). In fact, quantitative methodology as the one used for this study has been used in several scientific inquiry studies relying on survey data (Allen, M., 2017).

Data Collection

The data for this study was collected using an online questionnaire. The online questionnaire was used because it is effective, convenient, fast return rate, and reduced expenses (Handscomb, L., et al, 2016). The online survey consisted of questions that focused on project delays due to material supply disruption in process and equipment divisions (Divisions 40 to divisions 48) of the CSI's Master Format. The questionnaire surveys were distributed and completed online since this technique would be the most beneficial and appropriate route to acquire a fast response during this COVID-19 pandemic. The questionnaire was developed in Qualtrics following the Human Subject Research protocol approved by two universities in Texas. The data collection focused on information related to the COVID-19 pandemic delay in the projects, the duration of the active projects during the pandemic, and the reasons behind the delay.

The questionnaire was distributed during the Fall 2020 and Spring 2021 to fifty construction company executive members. Among them, the data valid for this study were collected from twenty-eight executive members in the United States. The data collected respondents were professionals who are mostly experts in commercial construction projects in addition to other construction sectors.

Questionnaire Survey

The questionnaire consisted of three major sections: demographic information, material delay information, and project delay impact information. The survey focused on construction delays due to material disruptions among eight process equipment divisions of the CSI Master Format. The eight process equipment divisions are Division 40- Process Interconnections, Division 42- Process heating, cooling, and drying equipment, Division43- Process gas and liquid handling, purification, and storage equipment, Division 44- Pollution and waste control equipment, Division 45- Industry-specific manufacturing equipment, Division 46-Water, and wastewater equipment, as well as Division 48- Electrical power generation.

Results

The survey was filled out by 20 General Contractors, 5 Sub-Contractor, and 3 consulting firms. There was a good distribution of respondents with ages between 25 years old and more than 50 years old. Thirty-five and seven-tenths of a percent (35.7%) of the respondent were between 25 and 39 years old with the majority of the respondents between 40 years old and more than 50 years old as shown in Table 1.

Table 1

Survey Demography

Age	Frequency	Percent	Accumulated Percentage
25-29 years old	1	3.6	3.6
30-34 years old	5	17.9	21.5
35-39 years old	4	14.3	35.7
40-44 years old	5	17.9	53.6
45-49 years old	4	14.3	67.9
50 years old or more	5	17.9	85.7
No Response	4	14.3	100.0
Total	28	100.0	100.0

Thirty-nine and three-tenths of a percent (39.3%) of the respondents had fifteen (15) years of work experience or less with the majority of the respondents (60.7%) having fifteen (15) years or more of work experience as shown in Table 2. The fifteen years or more of work experience is important for this study as it indicates that the responses came from highly knowledgeable and informed construction professionals as supported by studies that indicated that work experience is the greatest predictor of competitive intelligence (Pellissier, R., & Nenzhelele, T., 2013). Competitive intelligence refers to the ability of an individual to gather, analyze, and use information collected for businesses' competitive advantages (Bloomenthal, A., 2021).

Table 2

Work Experience in Construction

Age	Frequency	Percent	Accumulated Percentage
1 to 5 years	1	3.6	3.6
5 to 10 years	7	25.0	28.6
10 to 15 years	3	10.7	39.3
15 to 20 years	2	7.1	46.4
more than 20 years	11	39.3	85.7
No Response	4	14.3	100.0
Total	28	100.0	100.0

Based on the online survey question "How many calendar days (on average) did the COVID-19 pandemic delay your active projects?" the result shows that the projects were delayed from less than 5 days to more than 56 days as shown in Figure. 1. Among those projects delayed, thirty-one percent (31%) of the projects were delayed between 6 to 15 days, twenty-seven percent(27%) of the projects were delayed less than 5 days, and nineteen percent (19%) of the projects were delayed 26 to 35 days. This result is consistent with other references that indicate that in 2020 the average construction job delay was 17.47 days (Robinson, S., 2022). This study also expands the current knowledge by presenting the variability and distribution of the number of days delayed due to COVID-19. This could be attributed to the fact that during the COVID-19 pandemic, there were travel restrictions including the closure of the facilities that distribute metals and products that are related to long lead time. Manufacturing companies say they received supplier deliveries more slowly in the month of May than in April (Wood, 2021).

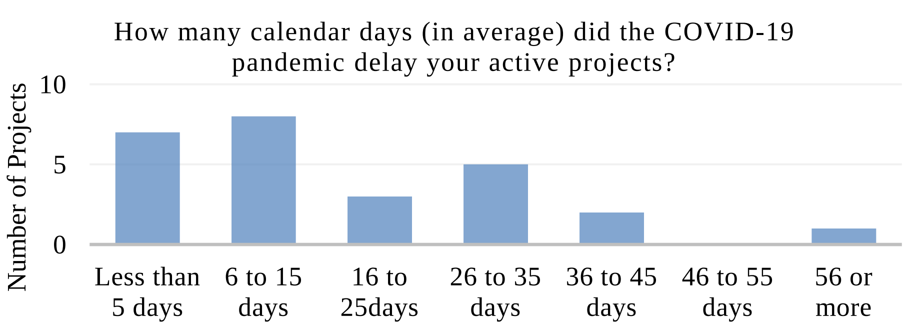

Figure 1. Active project delayed due to the COVID-19 pandemic

Analysis And Discussion

Material Delays by CSI Divisions

The materials delay for the CSI Master Format process equipment divisions (Divisions 40, 41, 42, 43, 44, 45, 46, 48) is shown in Figure 2. The materials delay in the process equipment subgroups varied significantly ranging from 0 to 50 days. For example, the median delay for materials associated with Division 40 - Process Interconnections and Division 43 – Process Gas and Liquid Handling, Purification and Storage Equipment was between 6 and 15 days (blue bar in Figure 2); while the median delay for materials associated with Division 48 — Electrical Power Generation was between 21 to 31 days as shown in Figure 2. Furthermore, the variability of the delays was significantly different among the different divisions. For example, the number of delay days in the 25% percentile (shortest delay) of Division 40 was between 0 and 5 days (green line in Figure 2), while for Division 48 was between 4 and 13 days. On the opposite side of the spectrum, the number of delay days in the 75% percentile (longest delay) of Division 40 was between 11 and 21 days (red line in Figure 2), while for Division 48 was between 41 and 50 days. This significant delay variability (among the different divisions) found in this study, could be attributed to the different supply chain used in the manufacture of the different construction components. Reports show that fabricated metal products, transportation equipment, and chemical products had the slowest deliveries (Wood, 2021) which supports the results of this study. Furthermore, this information is very important for decision-makers to identify the divisions that required the earliest intervention in future supply disruptive events.

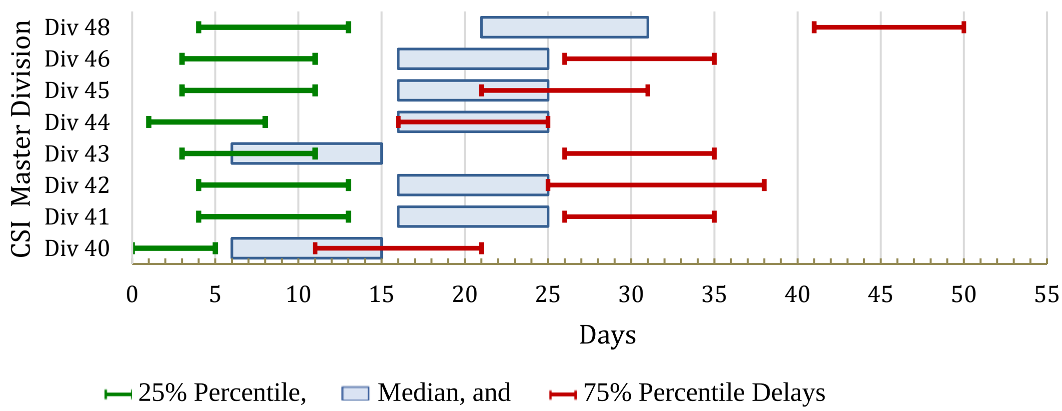

Figure 2. Processing Equipment Division

Conclusions

This study collected and analyzed the survey response from 28 construction companies (20 General Contractors, 5 Sub-Contractor, and 3 consulting firms) regarding how materials disruption in supply caused delays in projects and impacted their cost in the United States. The findings show that COVID-19 impacted the most of the materials supply chain related to CSI Division 48 – Electrical power generation followed by Division 41 – material processing and handling equipment, Division 42 – process heating, cooling, and drying equipment, and other divisions such as Division 44, 45, and 46. These delays could be attributed (as Research indicates) to the order backlogs that expanded for 11 straight months after the COVID-19 shut down in March 2020. Additionally, supplies shortage, and logistic issues had a greater impact on the project schedule during this pandemic.

The results of this study are consistent with the estimated construction job delay of 17.57 and expand it by presenting the variability and distribution of the number of days delayed due to COVID-19. It also shows the significant delay variability (among the different divisions) which is important information for construction decision-makers to make informed decisions regarding the part of the jobs (based on CSI Divisions) that will require the earliest intervention in future possible supply disruptive events. In short, the analysis and findings of this study help decision-makers to better understand the impact of COVID-19 to better find solutions to supply chain disruptions in the construction industry caused by possible future pandemics (or wars as the one currently in Ukraine). In the future, it would be interesting to study the changes that construction companies have made following the research findings of this and other papers.

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References

Al Amri, T., & Marey-Perez, M. (2020). Impact of Covid-19 on Oman's construction industry. *Technium Social Sciences Journal*, 9, 661-670

Allan-Blitz, L. T., Turner, I., Hertlein, F., & Klausner, J. D. (2020). High frequency and prevalence of community-based asymptomatic SARS-CoV-2 infection. *medRxiv*, doi:10.1101/2020.12.09.20246249

Allen, M. (2017). The SAGE encyclopedia of communication research methods (Vols. 1-4). Thousand Oaks, CA: SAGE Publications, Inc doi: 10.4135/9781483381411

Alsharef, A., Banerjee, S., Jamil Uddin, S. M., Albert, A., & Jaselskis, E., (2021). Early impacts of the COVID-19 pandemic on the United States construction industry. *International Journal of Environmental Research and Public Health*, 18 (4), p.1559.

Araya, F. (2021). Modeling working shifts in construction projects using an agent-based approach to minimize the spread of COVID-19. Journal of Building Engineering, 41, 102413 - 102413.

Ayodele, O. A., Chang-Richards, A., & González, V., (2020). Factors Affecting Workforce Turnover in the Construction Sector: A Systematic Review. *Journal of Construction Engineering and Management*, 146(2), 03119010.

Bloomenthal, A., (2021). Competitive Intelligence: Definition, Types, and Uses, Investopedia Business Essential.

Brown, K. (2019). For Generation Z, the value of a construction career is a no-brainer. Construction Dive. Accessed May 25, 2021. https://www.constructiondive.com/news/for-generation-z-the-value-of-a-construction-career-is-a-no-brainer/546099/.

Brown, S., Brooks, R., Dong, X. S. (2020). Impact of COVID-19 on Construction Businesses and Productions. CPWR Data Bulletin. November 2020. Accessed May 15, 2021. https://www.cpwr.com/wp-content/uploads/DataBulletin-November2020.pdf .

Butt, A., (2022). Understanding the implications of pandemic outbreaks on supply chains: an exploratory study of the effects caused by the COVID-19 across four South Asian countries and steps taken by firms to address the disruptions. International Journal of Physical Distribution & Logistics Management, 52(4), 370–392. https://doi.org/10.1108/IJPDLM-08-2020-0281

CDC (Centers for Disease Control and Prevention)(2021) “What construction workers need to know about COVID-19”. https://www.cdc.gov/coronavirus/2019-ncov/community/organizations/construction-workers.html. Accessed June 15, 2021.

CDC (Center for Disease Control and Prevention) (2022a) “Covid Data Tracker” https://covid.cdc.gov/covid-data-tracker/#datatracker-home. Accessed October 12, 2022

CDC (Center for Disease Control and Prevention) (2022b) “Vaccines for COVID-19” https://www.cdc.gov/coronavirus/2019-ncov/vaccines/index.html?s_cid=11759:cdc%20covid%20guidelines:sem.ga:p:RG:GM:gen:PTN:FY22 Accessed October 12, 2022

Choi, S. D., Rosenthal, D., & Hauser, S., (2013). Health and safety issues of older workers surveyed in the construction industry. *Industrial and Systems Engineering Review*, 1(2), 123-131.

Choi, S. D., & Staley, J. A., (2021). Safety and Health Implications of COVID-19 on the United States Construction Industry. *Industrial and Systems Engineering Review*, 9(1), 56-67.

Denny-Smith, G., Sunindijo, R. Y., Loosemore, M., Williams, M., & Piggott, L. 2021. How Construction Employment Can Create Social Value and Assist Recovery from COVID-19. *Sustainability*, 13(2), p.988.

Esa, M. B., Ibrahim, F. S. B., & Kamal, E. B. M. (2020). Covid-19 pandemic lockdown: The consequences towards project success in Malaysian construction industry. *Advances in Science, Technology and Engineering Systems Journal*, 5(5), 973-983

Fennelly K. P. (2020). Particle sizes of infectious aerosols: implications for infection control. The Lancet. Respiratory medicine, 8(9), 914–924. https://doi.org/10.1016/S2213-2600(20)30323-4

Gamil Y., & Alhagar A., (2020). The Impact of Pandemic Crisis on the Survival of Construction Industry: A Case of COVID-19, *Mediterranean Journal of Social Sciences* 11(4), 122-128

Gunduz, M., & Ahsan, B., (2018). Construction safety factors assessment through Frequency Adjusted Importance Index. *International Journal of Industrial Ergonomics*, 64, 155-162

Handscomb, L., Hall, D.A., Shorter, G.W., & Hoare, D.J. (2016). Online Data Collection to Evaluate a Theoretical Cognitive Model of Tinnitus. American journal of audiology, 25 3S, 313-317 .

Heigl C. (2018). 7 Major Trends That Will Impact the Construction Industry. *Construction Industry News*. Accessed June 20, 2021.

Kaushal, V., & Najafi, M. (2021). Strategies to mitigate COVID-19 pandemic impacts on health and safety of workers in construction projects. *Civil Engineering Beyond Limits*, 2, 1-8.

Kisi, K. & Sulbaran, T., (2022). Construction Cost and Schedule Impacts Due to COVID-19. Journal of Legal Affairs and Dispute Resolution in Engineering and Construction, 14(4). https://doi.org/10.1061/(ASCE)LA.1943-4170.0000565

Loosemore, M., & Malouf, N., (2019). Safety training and positive safety attitude formation in the Australian construction industry. Safety Science, 113, 233-243

McMaster, M., Nettleton, C., Tom, C., Xu, B., Cao, C., & Qiao, P. (2020). Risk management: Rethinking fashion supply chain management for multinational corporations in light of the COVID-19 outbreak. Journal of Risk and Financial Management, 13(8), 173.

Namian, M., Albert, A., Zuluaga, C. M., & Behm, M. (2016). Role of safety training: Impact on hazard recognition and safety risk perception. *Journal of construction engineering and management*, 142(12), 04016073

Pandit, B., Albert, A., Patil, Y., & Al-Bayati, A. J. (2019). Impact of safety climate on hazard recognition and safety risk perception. *Safety Science*, 113, 44-53

Pasco, R. F., Fox, S. J., Johnston, S. C., Pignone, M., & Meyers, L. A. (2020). Estimated association of construction work with risks of COVID-19 infection and hospitalization in Texas. *JAMA network open*, 3(10), e2026373-e2026373.

Pellissier, R., Nenzhelele, T. E. (2013). The impact of work experience of small and medium-sized enterprises owners or managers on their competitive intelligence awareness and practices. South African journal of information management, 15(1), 1-6.

Pujawan, I. N., & Bah, A. U. (2022). Supply chains under COVID-19 disruptions: literature review and research agenda. In Supply Chain Forum: An International Journal (Vol. 23, No. 1, pp. 81-95). Taylor & Francis.
Olanrewaju, A.L., AbdulAziz, A., Preece, C., & Shobowale, K.O. (2021). Evaluation of measures to prevent the spread of COVID-19 on the construction sites. Cleaner Engineering and Technology, 5, 100277 - 100277.
Okonkwo, C., Garza, R., Sulbaran, T., & Awolusi, I. (2022). A Review of Genetic Algorithm as a Decision-Making Optimization Tool in Project Management. EPiC Series in Built Environment, 3, 254-262.
Robinson, S., (2022) Mining the data field: 5 construction materials causing delays (+4 ways to manage), Buildertrend
Rodriguez, J. (2019). Managing Five Generations at the Construction Site. Communication and Integration Are Essential for Success. Updated March 2019. Accessed June 02, 2021. https://www.thebalancesmb.com/managing-different-generations-in-construction-4137829
Shen, H., Fu, M., Pan, H., Yu, Z., & Chen, Y. (2020). The impact of the COVID-19 pandemic on firm performance. *Emerging Markets Finance and Trade*, 56(10), 2213-2230.
Susanti, R., Fauziyah, S., & Pramesti, P. U. (2021). Lesson from pandemic Covid-19 for sustainability construction in Indonesia. In AIP Conference Proceedings (Vol. 2447, No. 1, p. 030013). AIP Publishing LLC.
Taqi, H. M. M., Ahmed, H. N., Paul, S., Garshasbi, M., Ali, S. M., Kabir, G., & Paul, S. K. (2020). Strategies to manage the impacts of the COVID-19 pandemic in the supply chain: implications for improving economic and social sustainability. Sustainability, 12(22), 9483.
Uddin, S. M. J., Albert, A., Alsharef, A., Pandit, B., Patil, Y., & Nnaji, C. (2020). Hazard Recognition Patterns Demonstrated by Construction Workers. *International Journal of Environmental Research and Public Health*, 17(21), 7788
Valle, G., (2022). Is Construction a Service Industry? , BuilderSpace, https://www.builderspace.com/is-construction-a-service-industry#:~:text=As%20far%20as%20construction%20is%20concerned%2C%20is%20it,construction%20do%20meet%20the%20definition%20of%20service-based%20operations.
Yu, C., Lei, Q., Li, W., Wang, X., Liu, W., Fan, X., & Li, W. (2020). Clinical Characteristics, Associated Factors, and Predicting COVID-19 Mortality Risk: A Retrospective Study in Wuhan, China. American Journal of Preventive Medicine, 59, 168 - 175.
Zidan, A., Mousa, A., & Mahgoub, M., (2013). A survey-based vision for restructuring concrete business in the new residential communities in Egypt. *Industrial and Systems Engineering Review*, 1(2), 162-172.

Mapping Building Information Modeling Capabilities with the Information Needs of Studies of Domestic Arthropod Ecology

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The presence of arthropods is a fact of life in most buildings. While many are innocuous, some may have negative impacts on human occupants' health or economic well-being, like cockroaches, bed bugs, and pantry moths. Understanding the behavior and ecology of domestic arthropods is critical for indoor pest management and sustainability, and can support Integrated Pest Management (IPM) plans. Building Information Modeling (BIM) has the potential to serve as the data analysis and simulation platform for domestic arthropod studies. This research maps the current and potential functions of BIM to the needs of domestic arthropod studies, and conceptualizes a system architecture for a BIM-enabled simulation engine and platform for this purpose. This platform will contribute to the digitalization of structural IPM and will serve as an educational tool for professionals and students.

Key Words: Building Information Modeling (BIM), domestic arthropods, arthropod simulation platform, indoor environment, sustainability

Introduction and Literature Review

Arthropods impact human life in buildings in many ways beyond the pleasures of watching them. They may have negative impacts on occupants' health, such as with diseases spread by bed bugs (Eliopoulos, Tatlas, Rigakis, & Potamitis, 2018). Cockroaches may cause sanitary problems and also negatively impact the mental health of occupants. Termites and other wood-boring insects can cause significant structural damage. Pantry pests may damage food. There is a factor of fear and disgust among humans for some arthropods, such as spiders (Vernon & Berenbaum, 2002). There can also be significant economic impacts in commercial or industrial settings. These problems support a thriving structural pest management industry, worth an estimated $10.4B in 2021 in the United States (Pest Control Technology, 2022).

Many strategies and techniques exist for pest management, depending on the context and the pests (e.g. Rajendran, 2020). However, a well-established framework for developing sustainable pest management plans is Integrated Pest Management (IPM). IPM is a holistic approach, which focuses on prevention. It can include evaluations of the building system and occupant behaviors, monitoring of pest presence and activity, thresholds or triggers for action, and actual control actions. Understanding what conditions will lead to pest populations or damage crossing the threshold for control actions is crucial to effective prevention. IPM planning is ideally begun during building design, and there are a variety of guides available for best practices at the design, construction, and operation phases of a building (e.g. Geiger & Cox, 2012).

Building Information Modeling (BIM) is a technology and process that enables analyses of construction processes and products through visualization and simulation (Sacks et al. 2018). BIM has been used for creating and managing information in the design, construction, and facilities management (FM) phases (Autodesk, 2022). While BIM's applications in design and construction are relatively well developed, its applications in the FM domain are still in early stages of development (Sacks, Eastman, Lee, & Teicholz, 2018; Teicholz, 2013). In the last decade, researchers have begun to explore how BIM can be utilized to assist FM tasks, such as providing information and more automated means and methods for building operation and maintenance (Gao & Pishdad-Bozorgi, 2019; Pishdad-Bozorgi, Gao, Eastman, & Self, 2018). With the capability to model parametric objects, BIM is more than a design tool and can be used for multiple purposes of building analysis. BIM software tools have interfaces to other applications such as those for energy analysis and cost estimation (e.g. Carvalho, Almeida, Bragança, & Mateus, 2021; Jalaei & Jrade, 2014). Using BIM, the relationships between components can be defined and stored in the attributes of each component. Using visualization capabilities and 4D simulation (Gledson & Greenwood, 2017), BIM can effectively communicate key building issues related to scheduling and sequencing (Badrinath, Chang, & Hsieh, 2016). BIM also has decision support capabilities, including clash detection (Hu, Castro-Lacouture, & Eastman, 2019), rules checking and validation (Lee, Eastman, Solihin, & See, 2016), change tracking over time (Kensek, 2015), and cost management with 5D BIM (Smith, 2016).

Internet of Things (IoT) is a unified framework for developing a common operative picture and control systems for a building through interconnected sensing and actuating devices (Gubbi, Buyya, Marusic, & Palaniswami, 2013). IoT consists of technologies such as sensing technologies, identification and recognition technologies, position technologies, data processing solutions, communication technologies and networks, and software and algorithms (Čolaković & Hadžialić, 2018). IoT and BIM integration can be used to create a digital twin for a building (Mohammadi & Taylor, 2020; Tang, Shelden, Eastman, Pishdad-Bozorgi, & Gao, 2019; Taylor, Bennett, & Mohammadi, 2021), which enables the real-time data generation, analysis, and control of building systems. Successfully integrating BIM and IoT can yield real-time data for building systems, indoor environments, and occupant behavior and preference.

BIM has been used as a data platform for FM (e.g. Gotlib, Wyszomirski, & Gnat, 2020; Nour, 2010). Wang et al. (2013) developed a framework for engaging FM considerations in the design stage through BIM. In their research, BIM was used as a visual model and a database to provide integrated data for FM in the design stage throughout the building lifecycle. Kamal et al. (2021) described an integrated BIM-based framework for effective FM in hospital buildings. They utilized BIM to obtain consistent building information, visualized data, and quick data access. Kang and Choi (2015) developed a BIM database to connect external FM data with BIM data and provide relevant data based on user requests. Relying on BIM as a data source, an approach was presented by Hijazi et al. (2012) to obtain information on interior utilities. They mapped the semantic and connectivity information of BIM onto a new model called Network for Interior Building Utilities, which can provide a flexible way to manage interior utility network information. Ma et al. (2021) described a metadata-based image retrieval system by leveraging BIM and Geographic Information Systems

(GIS) to obtain image information rapidly. In their research, BIM is utilized as a data platform for FM photos. Dong et al. (2014) developed a BIM-enabled information infrastructure to maintain data integrity for energy-saving applications.

Simulation engines have been developed using BIM for research studies in the FM domain. Wang et al. (2013) utilized BIM to predesign and simulate the maintenance work in FM. Kamal et al. (2021) created a 4D simulation model with BIM to visually illustrate the process of repairing failed equipment and zones affected by repair tasks. To understand the decision-making process of an endangered person in an emergency, Rüppel & Schatz (2011) employed BIM as a simulation engine to create emergency scenarios in a video game and simulate human behavior. Chen et al. (2014) used BIM to conduct firefighting simulations for reducing response time by helping firefighters quickly locate ladder trucks.

A BIM-IoT-based software tool has the potential to be a powerful tool for the critical FM task of pest management. Currently, BIM has never been used to support domestic arthropod-related research, education, or practice (such as pest management). This research aims to partially fill this gap by exploring the feasibility of using BIM for domestic arthropod studies, and creating a knowledge foundation for developing BIM-based data analysis and simulation platforms for them. To accomplish this, this research maps the information needs of domestic arthropod studies onto BIM's current and potential functionalities. It then creates a conceptual framework for a BIM-enabled simulation platform with functionalities for recording data, simulation for studies of arthropod behavior and ecology, supporting IPM during design and FM, and providing educational tools.

Methods

We identified the information related to environmental characteristics that is necessary for general study of behavior and ecology of domestic arthropods using basic knowledge of ecology and structural entomology. We then developed a comprehensive list of relevant elements of single-family residential structures. Using this list, we mapped the ways in which BIM and IoT can provide and manage the information needed for studying domestic arthropod behavior and ecology. We organized this mapping into four categories based on our synthesis of the disciplinary intersections, including 1) food sources, 2) water sources, 3) space for physical shelter, nesting or hiding, and 4) transport paths for hunting, socialization, and seeking new territory.

Results

BIM has parametric modeling capabilities that allow objects to be defined by their properties in the building model. The properties of an object in BIM can define its size, materials, location, relations with other objects, etc. Software applications, in the form of Revit plugins, for example, can be developed to automate the data extraction process (e.g. Chen & Nguyen, 2019; Suprabhas & Dib, 2017; Zotkin, Ignatova, & Zotkina, 2016). These capabilities provide as much detail on objects, materials, open space, and spatial relations as can be recorded in a BIM; and, allow a complete digital model of all static elements of a building, thus defining the physical spaces in which arthropods exist.

BIM provides static building data, while IoT can provide real-time data generated by sensing devices. IoT-enabled BIM, serving as the digital twin, is able to represent real-time data for indoor environments, building systems status, and occupant behaviors and preferences (e.g. Miller et al., 2021; Zibuschka, Ruff, Horch, & Roßnagel, 2020). For example, continuous sensor readings can provide real-time data about the temperature and humidity in different building spaces. By analyzing the data collected with IoT devices, we can also identify occupant behavior patterns, such as when and how often occupants clean their houses, and where and when occupants feed their pets. These capabilities can provide a complete digital model of all dynamic elements of a building and some about its occupants and their behaviors.

We categorized building-related information needs for domestic arthropod studies into four groups: food sources, water sources, space, and transport. Detailed explanations of each are described in each section of the BIM mapping. Much of the environmental information useful for studying arthropods can be readily acquired through a BIM database, using existing capabilities. Table 1 shows the mapping results between information needs in domestic arthropod studies and BIM capabilities.

Food

Arthropods may obtain food from a variety of sources in a building, depending on the needs of each species. We identified building materials, components, or objects in a building space that could provide food for any arthropods, as well as any the food created or brought by human occupants. Sources may include: structures and components with organic materials such as wood beams and wood furniture; primary producers and decomposers growing directly on structures such as fungi on wet drywall or algae on a consistently damp windowsill; food intended for human consumption; food waste and spillage created by occupants such as food litter in a trash can; and bodies and shed body parts from occupants such as human blood and skin cells.

Food sources related to building components, can be determined directly from BIM. For instance, some building elements are made of wood, which provides food for termites. We can acquire relevant information, such specific wood types and locations, from BIM, use this to determine potential food sources. Similarly, we can use BIM elements paired with IoT sensing of moisture to determine possible growth areas for mold. The behavior of human occupants cannot be acquired from BIM directly; but can be determined from sensing data generated by IoT. For example, some food sources are created by occupants, such as meals left out, or dishes not being cleaned. By analyzing the IoT usage data of appliances (e.g., dishwasher), utilities (e.g., water tap), and indoor environment (lighting, sound, humidity, etc.), a system built upon BIM can recognize potential food sources.

Water

Arthropods that need to drink can obtain moisture from a variety of sources among building systems and components. Water can be obtained from plumbing systems and condensation. Condensation is produced with temperature and humidity changes, and we can identify the components that may produce condensation by analyzing the real-time IoT sensor readings. High-risk areas for condensation, and the locations of plumbing system components, drains, and taps can be extracted with BIM existing functions based on location and type. Humidity is also important for many arthropods, particularly those like dust mites that obtain their water from the air. This can be determined from IoT sensor readings.

Space

Arthropods occupy space, and may need a variety of different spatial characteristics depending on the needs of any given species. Spatial characteristics and exposure to light, temperature, air currents, and open areas define types of exposure. We divided space in buildings into four sub-categories according to exposure: fully protected spaces, partially protected spaces, exposed spaces with surfaces, and open areas. The fully protected spaces and partially protected spaces are most often used for shelters by species that spend some or all of their time hidden, such as cockroaches. Partially protected spaces are also used as shelters but are not fully enclosed. These can be structures and objects, including the gaps between structural or decorative elements like sideboards and windowsills, and may be useful for temporary hiding or web building in transition zones. Exposed spaces with surfaces are utilized when leaving shelter, or by species that may not seek shelter. Open areas are the voids in a building where arthropods can easily fly. Each type of space can be derived from BIM elements with full 3D models, supported by information about environmental conditions and sources of light.

Transport

Arthropods require passage between spaces for hunting, finding mates, or seeking new territory or resources. They also may need ways of entering or exiting a building. Ambulatory arthropods require contiguous surfaces to move between zones. Flying arthropods are able to move through zones large enough to accommodate flight, indicated by open spaces and large voids connecting areas in a building. Access and exit points for a building may include utility passages, doors, windows, and vents. These are obtainable from BIM functions with spatial relations and component models.

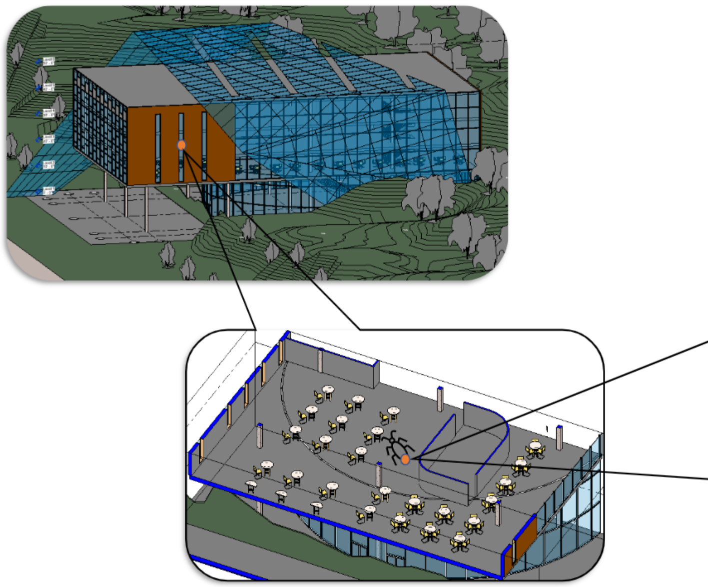
Discussion

We have conceptualized a BIM-enabled simulation platform with data storage and simulation functions for researchers to study domestic arthropods and to serve as an educational tool for biology students. Figure 1 shows an illustration of this framework for a BIM-enabled simulation platform. It would contain a 3D building information model, and the arthropod community's data. It would also contain a simulation engine (Figure 2), which would incorporate arthropod behaviors as simulation algorithms, a visualization of arthropod population dynamics, distribution, and possible movement patterns.

In the platform, the inputs for simulation include: food sources, water sources, space, and transport paths. Some of these data can be directly extracted from the IoT-BIM model. For example, some wooden structural materials can be a food source for some insects, and the data of the element locations, quantity, material properties can be extracted from the BIM model. A particular space's temperature and humidity can be extracted from the IoT sensing data. Some other input data may need manual input, such as food waste created by occupants and observations of insects.

The outputs of the simulation engine include: 1) the approximate current populations of species living in a particular building space during a given time period; 2) species population dynamics; 3) arthropod community dynamics; and 4) current and potential areas for expansion and exploitation.

These outputs have potential use in study of domestic arthropod behavior and ecology. They also have potential to be useful in designing and implementing IPM plans. IPM plan creation requires the identification of vulnerabilities and expectations for pest activity, so using these models to simulate and predict arthropod activity in a building as early as the design phase can have major downstream effects. Similarly, these outputs in conjunction with IoT monitoring will provide a major aid in IPM practice in FM. This tool can also support research into arthropod behavior and ecology in buildings, which will in turn support improvement to IPM practices.



Information	Details
Food Sources	
Materials	Wood / N/A
Location	Desk 21
Local Coordinates	(12, 45, 69)
Water sources	
Location	Pipe 15
Local Coordinates	(18, 66, 81)
Space	
Physical Shelters	
Location	Under Chair 18
Local Coordinates	<Matrix (3*8)>
Temperature	75 F
Humidity	81%
Other Space	
Room Number	5
Local Coordinates	<Matrix (3*8)>
Temperature	75 F
Humidity	80%
Transportation	
Hunting Zones	
Room Number	3
Moving Paths	<Matrix (3*N)>
Flying/Walking paths	
Room Number	3
Local Coordinates	<Matrix (3*N)>

Figure 1. A conceptual illustration of a BIM-enabled simulation platform

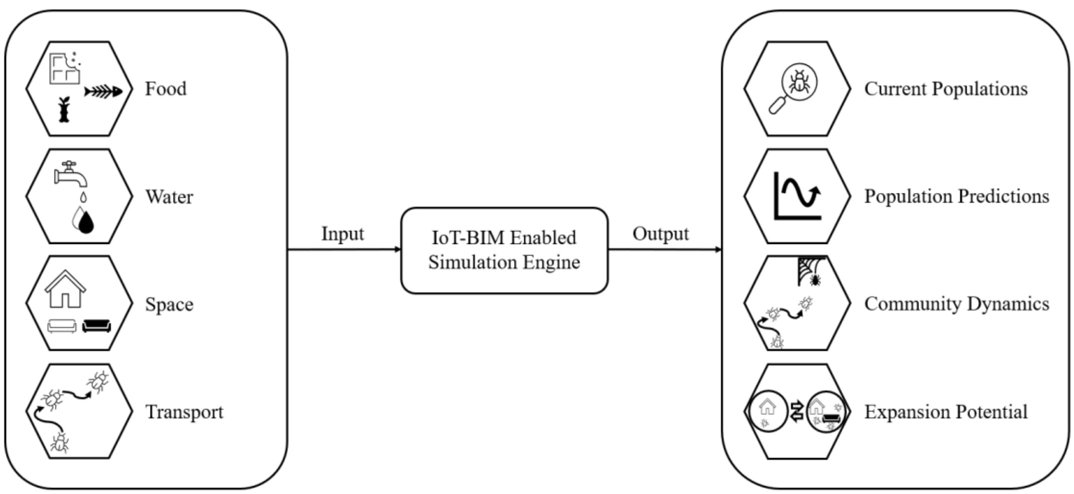


Figure 2. A conceptual simulation framework

Conclusions

This research maps BIM's capabilities with information requirements for studying and managing domestic arthropods. We have identified the information needs that can be obtained from an IoT-enabled BIM model and presented the mapping results in Table 1. This work provides a building block for establishing a BIM-enabled simulation platform for domestic arthropod study and management. The inputs for simulation include data about the arthropod's food sources, water sources, space, and transport. The outputs are predictions on arthropod behavior and ecology. The research team is currently developing a prototype for the simulation platform using the conceptual framework described in this paper. As new iterations of the tool are applied to specific organisms, additional variables and details will be developed and added. It is envisioned that this platform will serve as a research tool for arthropod researchers, as an educational tool for biology students, and provide support for IPM related FM tasks beginning in the building design phase, and carrying through the life of the facility.

References

Autodesk. (2022). BIM Benefits | Why Use BIM? | Autodesk. Retrieved October 30, 2022, from https://www.autodesk.com/industry/aec/bim/benefits-of-bim

Badrinath, C. A., Chang, Y.-T., & Hsieh, S.-H. (2016). A review of tertiary BIM education for advanced engineering communication with visualization. *Visualization in Engineering*, *4*(1), 1–17.

Carvalho, J. P., Almeida, M., Bragança, L., & Mateus, R. (2021). Bim-based energy analysis and sustainability assessment—Application to portuguese buildings. *Buildings*, *11*(6), 246.

Chen, L.-C., Wu, C.-H., Shen, T.-S., & Chou, C.-C. (2014). The application of geometric network models and building information models in geospatial environments for fire-fighting simulations. *Computers, Environment and Urban Systems*, *45*, 1–12.

Chen, P. H., & Nguyen, T. C. (2019). A BIM-WMS integrated decision support tool for supply chain management in construction. *Automation in Construction*, *98*, 289–301.

Čolaković, A., & Hadžialić, M. (2018). Internet of Things (IoT): A review of enabling technologies, challenges, and open research issues. *Computer Networks*, *144*, 17–39.

Dong, B., O'Neill, Z., & Li, Z. (2014). A BIM-enabled information infrastructure for building energy Fault Detection and Diagnostics. *Automation in Construction*, *44*, 197–211.

Eliopoulos, P., Tatlas, N.-A., Rigakis, I., & Potamitis, I. (2018). A "smart" trap device for detection of crawling insects and other arthropods in urban environments. *Electronics*, *7*(9), 161.

Gao, X., & Pishdad-Bozorgi, P. (2019). BIM-enabled facilities operation and maintenance: A review. *Advanced Engineering Informatics*, *39*, 227–247.

Geiger, C. A., & Cox, C. (2012). *Pest prevention by design: Authoritative guidelines for designing pests out of structures*. San Francisco.

Gledson, B. J., & Greenwood, D. (2017). The adoption of 4D BIM in the UK construction industry: An innovation diffusion approach. *Engineering, Construction and Architectural Management*.

Gotlib, D., Wyszomirski, M., & Gnat, M. (2020). A Simplified Method of Cartographic Visualisation of Buildings' Interiors (2D+) for Navigation Applications. *ISPRS International Journal of Geo-Information*, *9*(6), 407.

Gubbi, J., Buyya, R., Marusic, S., & Palaniswami, M. (2013). Internet of Things (IoT): A vision, architectural elements, and future directions. *Future Generation Computer Systems*, *29*(7), 1645–1660.

Hijazi, I. H., Ehlers, M., & Zlatanova, S. (2012). NIBU: A new approach to representing and analysing interior utility networks within 3D geo-information systems. *International Journal of Digital Earth*, *5*(1), 22–42.

Hu, Y., Castro-Lacouture, D., & Eastman, C. M. (2019). Holistic clash detection improvement using a component dependent network in BIM projects. *Automation in Construction*, *105*, 102832.

Jalaei, F., & Jrade, A. (2014). Integrating BIM with green building certification system, energy analysis, and cost estimating tools to conceptually design sustainable buildings. *Construction Research Congress 2014: Construction in a Global Network*, 140–149.

Kamal, Z., Taghaddos, H., & Karimi, H. (2021). BIM-based maintenance management system for healthcare facilities. *Journal of Performance of Constructed Facilities*, *35*(4), 04021036.

Kang, T.-W., & Choi, H.-S. (2015). BIM perspective definition metadata for interworking facility management data. *Advanced Engineering Informatics*, *29*(4), 958–970.

Kensek, K. (2015). BIM guidelines inform facilities management databases: A case study over time. *Buildings*, *5*(3), 899–916.

Lee, Y.-C., Eastman, C. M., Solihin, W., & See, R. (2016). Modularized rule-based validation of a BIM model pertaining to model views. *Automation in Construction*, *63*, 1–11.

Ma, J. W., Czerniawski, T., & Leite, F. (2021). An application of metadata-based image retrieval system for facility management. *Advanced Engineering Informatics*, *50*, 101417.

Miller, C., Abdelrahman, M., Chong, A., Biljecki, F., Quintana, M., Frei, M., … Wong, D. (2021). The Internet-of-Buildings (IoB)—Digital twin convergence of wearable and IoT data with GIS/BIM. *Journal of Physics: Conference Series*, *2042*(1), 012041. IOP Publishing.

Mohammadi, N., & Taylor, J. (2020). Knowledge discovery in smart city digital twins. *Proceedings of the 53rd Hawaii International Conference on System Sciences*.

Nour, M. (2010). A dynamic open access construction product data platform. *Automation in Construction*, *19*(4), 407–418.

Pest Control Technology. (2022). U.S. Structural Pest Control Market Surpasses $10.4 Billion, Specialty Consultants Reports. Retrieved October 30, 2022, from Pest Control Technology website: https://www.pctonline.com/article/pest-control-industry-surpasses-10-million-specialty-consultants-research-report/

Pishdad-Bozorgi, P., Gao, X., Eastman, C., & Self, A. P. (2018). Planning and developing facility management-enabled building information model (FM-enabled BIM). *Automation in Construction*, *87*, 22–38.

Rajendran, S. (2020). Insect pest management in stored products. *Outlooks on Pest Management*, *31*(1), 24–35.

Rüppel, U., & Schatz, K. (2011). Designing a BIM-based serious game for fire safety evacuation simulations. *Advanced Engineering Informatics*, *25*(4), 600–611.

Sacks, R., Eastman, C., Lee, G., & Teicholz, P. (2018). *BIM handbook: A guide to building information modeling for owners, designers, engineers, contractors, and facility managers*. John Wiley & Sons.

Smith, P. (2016). Project cost management with 5D BIM. *Procedia-Social and Behavioral Sciences*, *226*, 193–200.

Suprabhas, K., & Dib, H. N. (2017). Integration of BIM and utility sensor data for facilities management. In *Computing in Civil Engineering 2017* (pp. 26–33).

Tang, S., Shelden, D. R., Eastman, C. M., Pishdad-Bozorgi, P., & Gao, X. (2019). A review of building information modeling (BIM) and the internet of things (IoT) devices integration: Present status and future trends. *Automation in Construction*, *101*, 127–139.

Taylor, J. E., Bennett, G., & Mohammadi, N. (2021). *Engineering smarter cities with smart city digital twins*. American Society of Civil Engineers.

Teicholz, P. (Ed.). (2013). *BIM for facility managers*. John Wiley & Sons.

Vernon, L. L., & Berenbaum, H. (2002). Disgust and fear in response to spiders. *Cognition & Emotion*, *16*(6), 809–830.

Wang, Y., Wang, X., Wang, J., Yung, P., & Jun, G. (2013). Engagement of facilities management in design stage through BIM: framework and a case study. *Advances in Civil Engineering*, *2013*.

Zibuschka, J., Ruff, C., Horch, A., & Roßnagel, H. (2020). A human digital twin as building block of open identity management for the internet of things. *Open Identity Summit 2020*.

Zotkin, S. P., Ignatova, E. V., & Zotkina, I. A. (2016). The organization of autodesk revit software interaction with applications for structural analysis. *Procedia Engineering*, *153*, 915–919.

Table 1

Mapping between information needs in domestic arthropod studies and BIM capabilities

Type	BIM/IoT Type	Subcategory	General Description	Example Elements
Food	Structures	Materials	Digestible organic building materials	Wood foundation, siding
	Structures	Substrates for food growth	Moist areas that can grow mold, mildew, or bacterial films.	Wet drywall growing mold
	Furniture	Organic furniture	Furniture with organic components	Leather furniture upholstery
	Finishes	Organic finishes	Organic decorative items	Books, taxidermy, tapestry, art
	Finishes	House plants	House plants (or dried plants)	House plant
	Structures	Trap spaces	Places where arthropods tend to die	Window sill accumulating dead bugs
	Utilities	Standing water	Still water where things can grow	Spare bathroom, floor drain
	Occupants	Food	Storage or presentation of food	Pantry, dog food bowl
	Occupants	Food waste	Any storage of food waste	Kitchen trash receptacle
	Occupants	Pet waste	Any source of pet feces	Cat litter box
	Occupants	Bathroom waste	Removed elements of the body	Bathroom trash can
	Occupants	Occupant Body	Occupant bodies provide food	Human occupant, pets
	Occupants	Behaviors	Behaviors that make food sources available	Locations for food consumption, shedding of skin and hair
	Occupants	Hygiene	Cleaning habits	Vacuuming, dishwasher usage
Water	Structures	Condensation	Any location where condensation occurs	Leaky windows, poorly designed wall/vapor barriers
	MEP	Taps	Anywhere water is delivered.	Tap in sink
Space	Structures	Fully protected spaces	Gaps between structural or decorative elements	Space between cladding and sheathing, gaps behind sideboards
	Structures	Partially protected spaces	Areas that can be backed into but are still exposed.	Corners edges between wall and ceiling, windowsills
	Structures	Exposed spaces with a surface	No elements to back up against. Allow free moment by walking	Desk surface
	Structures	Fully open area	Spaces through which an insect can fly	Room space
Transport	Openings	Access points	Entry and exit for building	Door or window
	Structures	Walking paths	Contiguous surfaces	Walls, ductwork surfaces
	Structures	Flying space	Open space	Room space

A Review of Existing Commercial Mass Timber Buildings in the United States

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The proliferation of mass timber structures across the United States has begun. So much so, a comprehensive evaluation of key building attributes and identification of trends in built structures can be measured. This study utilizes a comprehensive market analysis of existing commercial mass timber structures to quantify important attributes to gain au fait and establish a baseline dataset. Specific interest lies in key areas, sustainability certification frequency and type, location, size, cost, and construction type. This study deploys descriptive statistics to evaluate 229 completed mass timber commercial projects across the United States. The study draws linkages and observes relationships between sustainability rating systems and mass timber structures, geographic concentrations, project cost, project size and height, building type, and building location. The expansion of mass timber is highlighted by the fact that nearly 80% of states across the country are home to a commercial MT building, with an average price per square foot of $344.89, and sustainability rating presence in over 30% of projects.

Key Words: Mass timber, sustainability, construction, United States, LEED

Introduction

Traditionally solely a European endeavor, mass timber has now proliferated across every region of the United States. Emanating from Austria in the early 1990's commercial applications started slowly, picking up when standards and "green" building practices started to gain traction (Gagnon, Bilek, Podesto, & Crespell, 2013). While Europe began mass adoption in the 1990's, the United States first mass timber projects did not start popping up until much later, around the early 2010s. The very first "mass" timber project in the US can be debated as nuances of building types gained the title of first; for example, the first high-rise (as defined by Emporis Building Standards) received approved permitting in 2016 (Lynch, 2017). Other sources point to early 2010's. Around 2013, the US had around twenty-six (26) mass timer structures. This number rose to around five-hundred and seventy-six (576) by 2017 and included all project types (residential, bridgework, small renovations, etc. (Thompson, 2021). By June 2022, 1,502 mass timber projects had been constructed or were in design in all 50 states, in the multi-family, commercial, or institutional (WoodWorks, 2022a).

As these projects grow in not only size (height and square feet), but breadth of geographic locations, we must take stock of their presence. The reasoning for such widespread growth is multi-faceted and complex; there are obvious reasons, and some that are not as clear. For example, mass timber's clear connection with sustainability has been a driver in the expansion of such projects (Abed, Rayburg, Rodwell, & Neave, 2022). Manpower efficiency gains in certain MT building types has been identified (Mirando & Onsarigo, 2022) along with pre-fabrication capabilities that dwarf the other construction methodologies. Other possible reasons include the aesthetics of exposed wood, the improved occupant health and well-being, the reduced jobsite noise, and advanced fire protection and seismic resistance (Think Wood, 2020).

Few seemed to predict the rapid adoption across the US, leaving large gaps and opportunities for researchers to catch up. Empirical studies have not attempted to evaluate the comprehensive grouping of US based projects. In addition to the rapid expansion, the sheer relative infancy of the technology commands further prodding. This study takes stock of a wide sample of mass timber structures across the county, providing important market indicators and trends across timber projects. A critical look at the trends and the current state of mass timber construction in the US can help inform decisions on when it may be advisable to utilize mass timber construction, and the impact of mass timber on the building construction industry.

Mass timber in the United States

Due to the technology's relative infancy in the United States, the preponderance of existing scientific literature is from regions outside of the US (Duan, Huang, & Zhang, 2022). The earliest relevant peer reviewed literature in the US discusses the applications of innovative wood for bridge systems in the U.S. (Moody, Ritter, & GangaRao, 1990). While most of the current literature in the United States lies in the form of professional publications and gray literature, there are various case studies in non-academic literature focusing on singular or small groupings of project performance (WoodWorks, 2022b). Mass timber adoption in the U.S. got to a slow start relative to other regions of the world. Some researchers have credited the initial slow adoption of mass timber in the U.S to practitioners' inexperience with the material and a lack of mass timber building construction projects (Ahmed & Arocho, 2022). However, as discussed in the previous section, the number of mass timber projects has seen exponential growth over the past few years. The increase and growth of mass timber knowledge and experience in the US over the past decade, and the availability of numerous case studies in these recent years, has made it possible for researchers to start filling the knowledge gap that had heretofore been difficult to bridge.

Environmental Impact of Mass Timber

The Global construction industry has a significant impact on the environment. The industry consumes as high as 40% of global energy and contributes to as high as 39% of global greenhouse gas (GHG) emissions through the heavy construction equipment used, transportation, and the manufacturing of building materials (Liang, Gu, & Bergman, 2021; Zaman, Chan, Jonescu, & Stewart, 2022). The industry is continually exploring ways to reduce its impact on the environment and contribute to more sustainable societies by promoting and implementing sustainable design and construction practices. These include embracing new sustainable materials, methods and technologies, and increasing efficiency on the jobsite. Mass timber has emerged as a viable alternative to the traditional, carbon-intensive construction materials, primarily concrete and steel (Zaman, Chan, Jonescu, & Stewart, 2022). According to an article published in the Forest Products Journal that studied the global warming impact of softwood dimension lumber produced from logs in the Pacific Northwest (PNW) and Southeast (SE) regions of the United States, less than 180 (129 in PNW and 179 in SE) pounds of carbon dioxide equivalent is released for each cubic meter of lumber produced, while the same cubic meter of lumber stores about 2,000 (1887 in PNW and 2061 in SE) pounds of carbon dioxide equivalent (Milota & Puettmann, 2017). This represents a net carbon benefit of nearly one ton of carbon dioxide equivalent per cubic meter of lumber produced. A marked contrast to the other building materials (concrete and steel) which result in significant carbon emissions and do not store any carbon dioxide equivalent (Atkins, Anderson, Dawson, & Muszynski, 2022).

Economic Viability of Mass Timber

Studies comparing the construction cost using mass timber to that of concrete or steel have yielded different results with a majority concluding that mass timber is marginally more expensive while several others have found that mass timber is a cheaper alternative (Ahmed & Arocho, 2020; Onsarigo & Mirando, 2021; Van der Westhuyzen & Wium, 2021). Suffice to say that there are many variables that differ from one project to the next, and with the technology still in developing (when compared to concrete and steel), and the lack of an established, efficient supply chain, mass timber projects are projected to be more competitive going forward.

The number of buildings that have been completed using mass timber as the primary structural material has seen exponential growth in the United States over the past decade. However, there is no published work observing the general attributes of the existing mass timber structures. This work attempts to bridge that gap by presenting the general attributes which may be useful in guiding and predicting progress in building with wood.

Methodology

The goal of this study was to evaluate the existing mass timber commercial buildings and define what the data trends show, in a manageable form. This aim aligns with utilizing descriptive statistics to summarize the vast data accumulated primarily from the Woodworks Innovation Network database. The Woodworks Innovation Network (WIN) is an online community created by WoodWorks to facilitate collaboration among professionals using innovative wood building systems and technologies. A solid understanding of the characteristics of existing mass timber buildings is foundational to drawing generalizations and mapping trends that can aid decision making. Descriptive statistics allows us to condense data in a more manageable form and is the first and crucial step in assessment (Kaur, Stoltzfus, & Yellapu, 2018). A review of such condensed data forms can reveal significant facts crucial for guidance in decision making.

Data Collection and Analysis

The dominant resource for mass timber structures in the United States is the WoodWorks Wood Products Council, the council provides resources for commercial mass timber projects in the form of project assistance, continuing education, design tools, and on-demand training. This study takes advantage of WoodWorks online project tool, WoodWorks Innovation Network (WIN). The WIN was created by WoodWorks to help facilitate collaboration among professionals using innovative wood building systems and technologies (WIN, 2022). The database is public and provides important information relative to mass-timber projects across the globe. The network is a voluntary system for compiling real data from mass timber project participants, but the submissions are screened and verified.

Data collection started on August 7th, 2022 and finished on August 15th, 2022 by accessing the WoodWorks Innovation Network database. System defined filter options were selected in the following order; Building System-“Mass Timber”, include “unclaimed projects”, Building type-Assembly (Worship, Restaurant, Theater), Business (Office), Civic (Recreational), Educational, Government, Hotel/Motel, Institutional, Mixed-Use, Multi-Family (Apartments, Condos). The remaining filters were not included in the database search; Custom Innovative Residential (6) Mercantile (7). Exclusion criteria were based on non-commercial and unique building categories. Examples of excluded projects include pedestrian bridges, small civic pergolas, renovations and new projects under 10,000 sq ft are examples of projects included in the database but excluded from this study.

Individual project data was extruded from the WIN as captured in an excel spreadsheet for further analysis. Predetermined attribute columns were created in the excel document and were infilled after assessing each of the 229 completed projects. The data was stored on a google drive and was evaluated for error and outliers. Findings and discussions are presented in the following section based off of the extrusion of data from this extensive database.

Findings and Discussions

After applying the filters listed above, the WIN yielded two hundred and twenty-nine (n=229) mass timber projects fitting this study's established criteria. Each section below outlines findings for each independent variable extracted from the network.

Building Attributes, Building Type and Building Materials

Starting with square foot size, our sample represents a total of 21,948,189 square feet; the average MT structure yields 95,884 sq ft of space. The largest mass timber project was Wal-Mart's Corporate Headquarters listed at 3,000,000 square feet. Height of the structures averages just over three (3) floors, with the tallest building being twenty-five (25) stories, but the majority (59) are single-story buildings (see Figure 1).

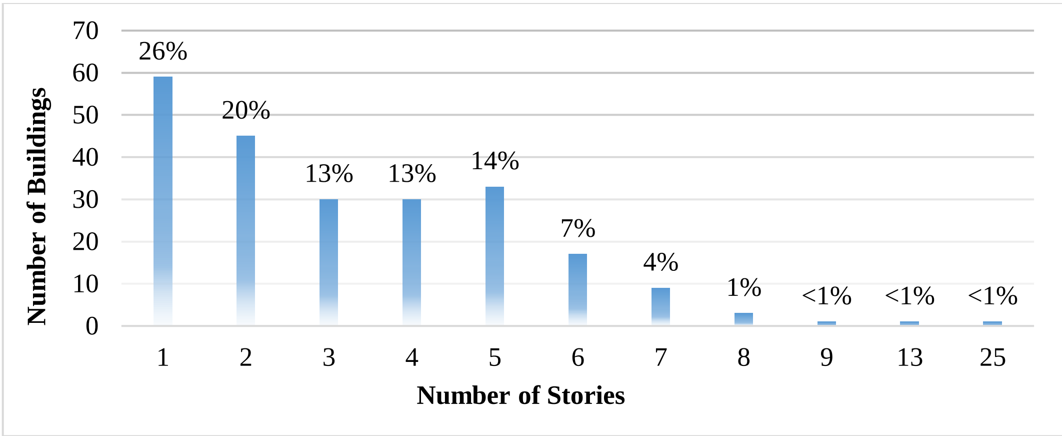

Figure 1. Frequency of Buildings by the Number of Stories

The WIN network produced thirteen categories of building types across our sample. The Business/Office category represents the leading building type at 30.56% (70 projects) of the sample.

Followed by the Educational building category at just under 22% (50 projects). In a tight grouping for third and subsequent places, Assembly at 10.04% (23 projects), Multi-family 9.6% (22 projects), and Mixed-Use 9.17% (21) projects make up a substantial portion of projects. The remaining projects are spread relatively thinly across the building types (see Figure 2).

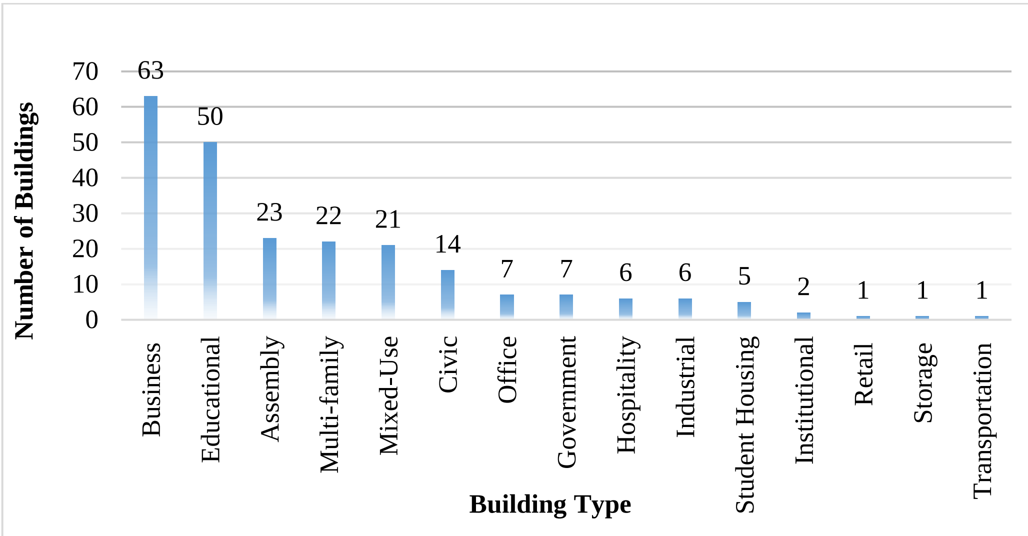

Figure 2 Building Type (Frequency)

Construction type is also an important attribute that offers insight to the project standards these structures adhere to. Surprisingly, V-B type construction leads the categories with 23% of projects (53) falling under the standards of a wood-framed building having no fire-resistance rating. This is deemed as the most commonly seen ISO 1 construction. This is a surprising finding especially since fire protection is a major concern of building with wood (Barber, 2018). Type III-B followed with just under 19% (43) defined as 'the roof/floors of combustible materials have no fire resistance rating". This is the most common of ISO 2 construction where the underside of the roof is exposed wood construction while the walls are other material such as masonry or concrete."

Geographical landscape

An impressive thirty-nine states (78%) across the United States have a minimum of one commercial mass timber project, with additional projects planned in some of the remaining states. Leaders at the state level are concentrated in the Pacific Northwest, topping out the top three with Oregon (48), followed by California (32), and Washington (29). The southeast of the country (NC, SC, and GA) also shows a high density of projects, accounting for almost 10% of the sample. Evaluating these structures through a geographic lens is integral in understanding the application of mass timber. While the Pacific region hosts most MT structures, the other regions are steadily picking up. We are seeing a trend typical of technology and development, where the coasts initiate new trends that eventually spread inward. Today, some manufacturers that were founded in the Pacific Northwest and Canada are seen to be expanding production and materials sources to the southeast to include southern yellow pine (Mesia, Mawema, & Farren, 2022). It is evident mass timber can be used in various climates and applications as evidenced by the sheer geographic distribution of projects and the growth trend is projected to continue going forward.

Cost

Due to privacy concerns, not every project provided cost information. Of the total sample n229, n92 provided cost information. One outlier was discovered and was omitted in terms of cost; the Nashville MLS Project included the total stadium cost of $300,000,000 in the project submission. However, just the canopies were mass timber structures, therefore it was omitted from the cost data. After outlier adjustment, the average completed price per square foot landed at $344.89. The most expensive project in the sample topped out at $130,000,000. Bigger projects exist in terms of dollar value but were not submitted. The smallest reported project landed at an even $1,000,000. See Figure 3 for the distribution across mass timber projects in the U.S.

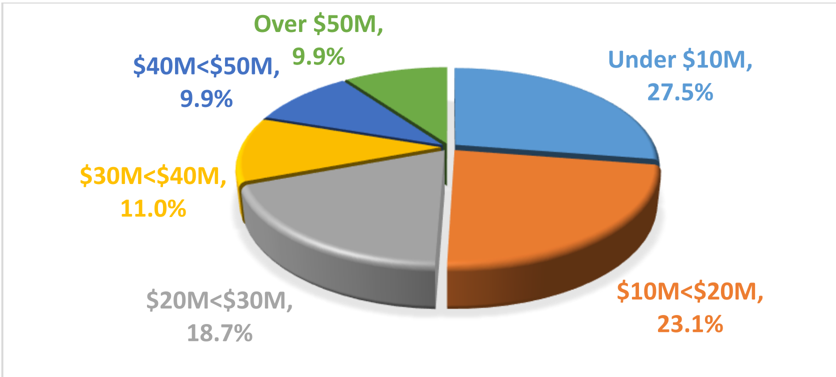

Figure 3. Construction Cost Distribution of Mass Timber Projects in the U.S.

More than half of the projects 50.6 percent were valued at below $20 million. The smallest categories were for projects values between $40 $50 million (9.9%) and those over $50 million (9.9%).

Sustainability

Table 1 represents the linkage between sustainability certification and mass timber construction.

Table 1.

Sustainability Certifications for Mass Timber Projects

Third-Party Sustainability Certification	Total Projects	Percent of MT Projects
LEED	89	38.86%
▪ Platinum Certification	19	08.30%
▪ Gold Certification	37	16.16%
▪ Silver Certification	17	07.42%
▪ LEED Certified	11	04.80%
▪ Certification Undetermined	5	02.18
Net-Zero Energy	9	03.93%
WELL	3	01.31%
Not certified	135	58.95%

Of the two-hundred and twenty-nine (229) buildings, 41% (95) reported achieving some level of third-party rated sustainability certification. Of that 41%, Leadership in Energy and Environmental Design is clearly the most prevalent system chosen, accounting for roughly 38.86% of that sample. Due to that fact, the breakout of level of certification within the LEED system seemed appropriate. When compared to the overall sample, the gold level of certification represents the majority at 16.16%, followed by Platinum at 8.3%, Silver at 7.42% and Certified at 4.8% of the sample. NZE certification follows far behind LEED at 3.93% and WELL certification, even farther behind, at 1.31%.

As more building designers, users, and investors have become more aware of the need to invest in sustainable options, we have seen an increase in green buildings. The number of mass timber buildings that reported as achieving some sustainability certification was anticipated (by the researchers) to be higher and is expected to rise as more buildings are erected. The 2019 Global Commercial Real Estate Services (CBRE) study on the U.S green building adoption index for office buildings found that only 4,879 or 13% of all commercial office buildings across the 30 largest U.S office markets were green certified (ENERGY STAR and LEED) (CBRE, 2019). Sustainability third party certification does not necessarily mean sustainability.

Conclusions and Limitations

This study successfully evaluated two-hundred and twenty-nine (229) existing mass timber projects across the United States identifying key building attributes, geographic locations, sustainability certification presence, cost, building size (height and square footage), amongst other important attributes. Important data trends in each key area were evaluated and presented within this study. Further research is required specific mass timber building sectors, which may be hindered by the scarcity of relevant, reliable and representative data. The recent exponential growth in number of projects, development team input and more concerted research efforts are required to gather more data for analysis. As this building type expands its influence across the country, a deeper understanding of all its facets is paramount. This study is a significant first step in presenting data that can inform decisions on when it may be advisable to utilize mass timber construction, the impact of mass timber on the building construction industry, and it can provide an indication of future trends relative to mass timber buildings. Additionally, the study can help in guiding the investment need relative to mass timber manufacturing in the United States.

The WIN database is the most extensive mass timber building database available; however, the database runs on voluntary project team submissions. In some cases, the database identifies projects that are built (or close to completion) but have not had voluntary project submissions from development teams. As a result, accurate and relevant information on such projects may be lacking. As at the time of this study, there are 140 “unclaimed” projects that have yet to be voluntarily submitted, and that cannot be included in the data even if they offer an opportunity for growth in the dataset. Soliciting this information form project teams and their subsequent involvement is integral to data sharing and improvement of the quality of data available. Project cost is one of those items that is not always available, and the reported number cannot be verified for accuracy. There are many reasons for this. For example, private development firms may not make their investment public, public projects (military, schools, government etc.) may publish overall project costs, including land acquisition, development fees, and other soft cost of a broad variety. For this study ninety-two (92), or roughly 40.17% of projects reported their cost to the WIN network. Year of completion also shares similar issues with cost in that certain outlets publish conflicting data. Since the WIN network reports on projects near completion, the date could still be in flux. This highlights how current the data is, and how rapid projects are being constructed. This important finding makes it difficult for complete date accounting, and even cross-referencing of databases (USGBC, WIN, grey literature, etc.)

The dataset established here offers a plethora of future empirical analysis opportunities. Regression analysis of the sample can take place to determine the impact of various parameters on other parameters. For example, price per-square foot data analyzed through the lens of LEED certification, height, location, and construction type. This requires further project information to fill the existing data gaps. Since a good number of projects have been developed recently, or are currently under development, complete data can be difficult to come by, highlighting the importance of this study, and the need for continued data gathering and analysis from researchers and practitioners.

This study highlights the need for continuing research in the field of mass timber. Numerous angles of inquiry and testing exist; sustainability, code compliance, engineering, cost, safety, efficiency, durability, etcetera, and they should be explored. Exploration of each area through various testing methods should continue to be encouraged and expanded upon. The options for inquiry are quite broad as evidenced by the literature, mass timber focused conferences, and journals. Now that structures are beginning to be occupied, life cycle analysis can and should be conducted to determine longevity of the structures, health and safety of occupants, energy performance, and maintenance requirements. Case studies of this nature are beginning to populate the literature, however, many more are needed.

References

Abed, J., Rayburg, S., Rodwell, J., & Neave, M. (2022). A Review of the Performance and Benefits of Mass Timber as an Alternative to Concrete and Steel for Improving the Sustainability of Structures. *Sustainability, 14*(9), 5570.

Ahmed, S., & Arocho, I. (2020). Mass timber building material in the U.S. construction industry: Determining the existing awareness level, construction-related challenges, and recommendations to increase its current acceptance level. *Cleaner Engineering and Technology*.

Ahmed, S., & Arocho, I. (2022). Identifying the Level of Awareness and Challenges to Adopt Mass Timber by the Construction Practitioners in the United States. *Construction Research Congress* (pp. 502-512). Arlington, Virginia: ASCE.

Atkins, D., Anderson, R., Dawson, E., & Muszynski, L. (2022). *2022 International Mass Timber Report.* Missoula, MT: Forest Business Network.

Barber, D. (2018). Fire Safety of Mass timber Buildings with CLT in USA. *Wood and Fiber Science, 50*, 83-95.

CBRE. (2019, October 17). *US Green Building Adoption Index for Office Buildings 2019.* Retrieved from cbre.com: https://www.cbre.com/insights/reports/us-green-building-adoption-index-for-office-buildings--2019

Duan, Z., Huang, Q., & Zhang, Q. (2022). Life cycle assessment of mass timber construction: A review. *Building and Environment, 221*, 109320.

Gagnon, S., Bilek, E., Podesto, L., & Crespell, P. (2013). Introduction to cross-laminated timber. In FPInnovations, E. Karacabeyli, & B. Douglas (Eds.), *CLT handbook: cross-laminated timber.* Pointe-Claire, Quebec Canada: FPInnovations.

Kaur, P., Stoltzfus, J., & Yellapu, V. (2018). Descriotive Statistics. *Biostatistics, 4*(1), 60-63.

Liang, S., Gu, H., & Bergman, R. (2021). Environmental Life-Cycle Assessment and Life-Cycle Cost Analysis of a High-Rise Mass Timber Building: A Case Study in Pacific Northwestern United States. *Sustainability, 13*(14), 7831. doi:https://doi.org/10.3390/su13147831

Lynch, P. (2017, June 9). The United States' First Mass-Timber Highrise Receives Planning Permission. *Arch Daily*. Retrieved from https://www.archdaily.com/873350/the-united-states-first-mass-timber-highrise-receives-planning-permission

Mesia, K., Mawema, V., & Farren, C. (2022, July 29). *Is Mass Timber the American South's Best Kept Secret? Not for Long.* Retrieved from Gensler: https://www.gensler.com/blog/is-mass-timber-the-american-souths-best-kept-secret

Milota, M., & Puettmann, M. E. (2017). Life-Cycle Assessment for the Cradle-to-Gate Production of Softwood Lumber in the Pacific Northwest and Southeast Regions. *Forest Products Journal, 67*(5/6), 331-342.

Mirando, A., & Onsarigo, L. (2022). Construction Productivity Comparison Between Cast-in-Place Concrete and Mass-Timber Framing: A Case Study of the Nation's Largest Mass-Timber Building. *ASC2022. 58th Annual Associated Schools of Construction International Conference. 3*, pp. 443-451. Atlanta, GA: EPiC Series in Built Environment.

Moody, R. C., Ritter, M. A., & GangaRao, H. (1990). Applications of Wood Materials for Innovative Bridge Systems. *Serviceability and Durability of Construction Materials* (pp. 423-432). New York, NY: American Society of Civil Engineers.

Onsarigo, L., & Mirando, A. (2021). Construction Productivity on Mass-Timber Framing: A Case Study of the Nation's Largest Mass-Timber Building. *Associated Schools of Construction. Great Lakes Region (Region 3)* (pp. 5-15). Downers Grove, Illinois: Associated Schools of Construction (ASC).

Think Wood. (2020, August). *Think Wood.* Retrieved from Mass Timber in North America: Expanding the possibilities of wood building design: https://www.thinkwood.com/continuing-education/mass-timber-north-america

Thompson, M. (2021, November 7). *Is mass timber the building material of the future?* Retrieved from PBS: https://www.pbs.org/newshour/show/is-mass-timber-the-building-material-of-the-future

Van der Westhuyzen, S., & Wium, J. (2021). A development cost comparison between a multi-storey mass timber and reinforced concrete building in South Africa. *Journal of the South African Institution of Civil Engineering, 63*(4), 35-44.

WIN. (2022). *WoodWorks Innovation Network (WIN)*. Retrieved from WoodWorks: https://www.woodworks.org/woodworks-innovation-network/

WoodWorks. (2022a, June). *U.S. Mass Timber Projects*. Retrieved from WoodWorks: https://www.woodworks.org/resources/u-s-mass-timber-projects/

WoodWorks. (2022b, August 16). *Mass Timber Business Case Studies*. Retrieved from WoodWorks: https://www.woodworks.org/resources/mass-timber-business-case-studies/

Zaman, A., Chan, Y.-Q., Jonescu, E., & Stewart, I. (2022). Critical Challenges and Potential for Widespread Adoption of Mass Timber Construction in Australia—An Analysis of Industry

OSHA-Investigated Electrocution Fatalities in the Construction Industry, 2015-2019

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Electrocutions are preventable, but still rank as the third leading cause of death on U.S. construction jobsites between 2015 to 2019. Eight percent (8%), or 401 of the 5,172 construction-related fatalities between 2015 and 2019 were due to *electrocution*. The research study presented in this paper reviewed the 310 investigations conducted by the Occupational Safety and Health Administration (OSHA) on the electrocution-related construction fatalities that occurred between 2015-2019 to identify potential trends for these fatal electrocution incidents. This study found that *contact with energized wires*, especially overhead powerlines, were responsible for the majority of construction worker fatal electrocutions. As a result, this study points out the most common electrocution hazards to help construction practitioners mitigate the propensity and frequency at which these fatal events occur.

Key Words: Electrocution, Fatal Four, OSHA, construction, safety, accidents

Introduction

Construction is an inherently dangerous industry that comprises a wide range of activities where workers are exposed to numerous occupational hazards (OSHA, 2021). Data obtained from the United States (U.S.) Bureau of Labor Statistics (BLS) indicate that over five thousand (5,172) U.S. construction workers died on-the-job between 2015 to 2019, which averages to nearly three construction fatalities per day (BLS, 2020). During this same time period, OSHA states the U.S. construction industry accounted for approximately 20% of all workplace fatalities in the United States, but only employed roughly 5% of the workforce (OSHA, 2021).

The Occupational Safety and Health Administration (OSHA) has identified four leading causes of fatalities in the construction industry (OSHA, 2011). They are referred to as either OSHA's "Fatal Four Hazards" or the "OSHA Focus Four Hazards". These top-4 hazards are 1) Caught-in/Between Hazards e.g. Trench cave-in, run-over/roll-over by equipment, caught-in equipment, crushed by material/equipment, asphyxiation, inhalation of toxic vapor, 2) Electrocution Hazards e.g. shock by touching exposed wires, shock by equipment/tool contacting power source, 3) Fall Hazards e.g. fall from ladder, fall from roof, fall through skylight, fall through unguarded floor opening, fall from structure, and 4) Struck-by Hazards Struck-by e.g. highway vehicle/construction equipment/falling material, power saw kick-back.

According to calculations conducted by the Center to Protect Workers' Rights (CPWR), the "Fatal Four" caused roughly sixty-five percent (65.2%, or 3,373 out of 5,172) of all construction fatalities for the years 2015-2019. *Falls* historically remain the leading cause of all deaths in construction, while *Struck-Bys* and *Electrocution*s, and *Caught-in/Betweens* are responsible for the second, third, and fourth most fatalities respectively (Brown et al., 2021).

While the percentages and number of fatalities distributed between the "Fatal Four" categories are useful, they don't provide enough detail to understand the work-related circumstances behind the worker deaths. A previous study conducted by Jenkins (2022) reviewed the *Fatality and Catastrophe Investigation Summaries* (OSHA 170 form) that were generated in response to construction-related fatality events investigated by OSHA between 2015 – 2019. The study identified nine types of events that led to worker electrocution fatalities. This study uses the nine fatal electrocution types to take a comprehensive look at the 310 electrocution-related fatality events investigated by OSHA between 2015 – 2019. By doing so, the factors and situations that lead to these incidents are highlighted. The findings are useful for construction practitioner's, supervisors, and field employees so that they can proactively identify existing or potential hazards in current or future construction work.

Literature Review

After a comprehensive review of recent safety-related literature, the authors found that limited research exists on electrocution-related fatalities in construction. Of these studies, only two utilized a similar research approach and analysis discussed in this paper.

Janicak (2008) investigated 492 construction worker fatalities involving contact with electricity between 2003–2006. *Contact with overhead power lines* was the most frequent fatal event in construction accounting for 47%, or 232 deaths out of the 492 electrocution fatalities during this four-year time period. *Contact with wiring, transformers, or other electrical components* was second-most with 34% (or 169 deaths out of the 492 total) of the fatalities.

A similar study by Zhao et. al (2014) examined data from FACE (Fatality Assessment and Control Evaluation) investigations conducted by National Institute of Occupational Safety and Health (NIOSH) for the 140 construction-related electrocution fatalities that occurred over 132 events between 1989-2010. This study found that *direct contact with electrical wire*, which included overhead and underground power lines, accounted for 40% of the construction fatalities, while *electrical incidents with construction equipment* accounted for 28% of the fatalities.

The Center for the Protection of Worker Rights (CPWR, 2018) analyzed data on fatal injuries and published the 6th Edition of *The Construction Chart Book: The U.S. Construction Industry and Its Workers*. This study found that between 2011-2015, deaths due to electrocution accounted for over eight percent (8.3%, 364 deaths) of all fatalities in construction. The CPWR study also stated that even though electrocution was more common among electrical workers, many electrocution deaths also occurred among non-electricians, such as construction laborers and roofers. The sources of electrocution deaths were quite different for electrical and non-electrical workers. While power lines and transformers were responsible for the majority of electrocution deaths among electrical workers, exposure to energized equipment/machines and tools caused a majority of the electrocution deaths among non-electrical workers.

Figure 1 shows the number of construction fatalities due to the "Fatal Four" for the years 2015-2019 (Brown, et al., 2021).

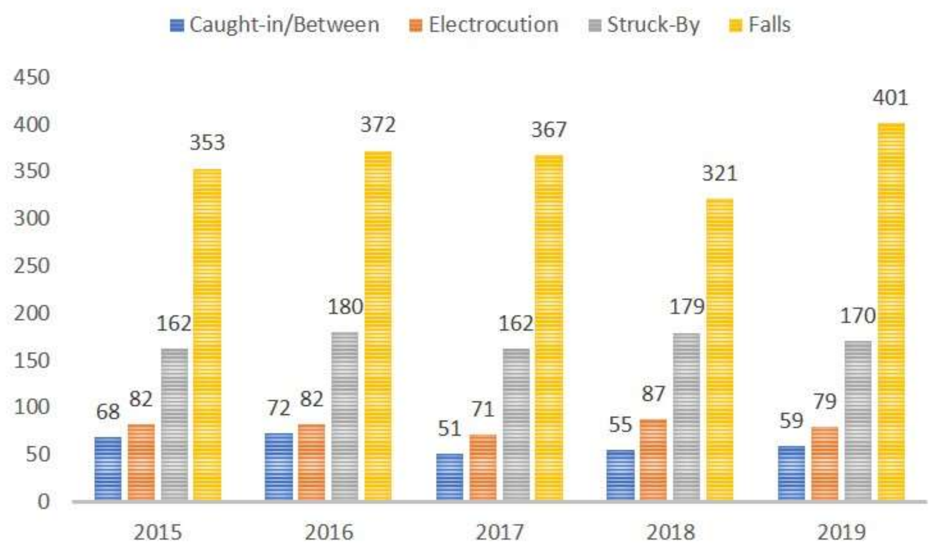

Figure 1. "Fatal Four" fatalities in construction, 2015-2019

As shown in Figure 1, *Electrocutions* were responsible for 401, or roughly 8% of the overall fatalities in construction between 2015 to 2019. During this same time period, OSHA was able to investigate 310 fatality events that led to 316 construction workers deaths during this time period. The multiple-fatality events for the *electrocution* events are discussed in Table 3 later in this paper.

While these studies demonstrate that working with or around electricity can be dangerous, the information does not reveal the whole story of these fatality events. More can be learned from a detailed look at the fatality investigation data.

Research Methodology

The Occupational Safety & Heath Administration (OSHA) conducts an inspection for most work-related fatalities and records a descriptive narrative of each investigated incident through the use of an *OSHA 170- Fatality and Catastrophe Investigation Summaries* form. A request was made under the *Freedom of Information Act* in September 2020 for the dataset of OSHA inspections of construction fatalities conducted between 2015 to 2019. The information dataset was sent as a Microsoft Excel spreadsheet file by the OSHA Directorate of Construction via email in May 2021. Microsoft Excel was used by the authors to sort and organize this information. Data received for this five-year time period was comprised of 2,938 lines of data which amounted to 2,789 construction fatalities investigated during this time period. This information was reorganized and sorted by the authors in order to group and analyze the information.

The OSHA inspection report dataset included the following elements:

- OSHA Inspection number for each fatality investigation

- North American Industry Classification System (NAICS) number of companies/industries
- Incident date and time
- Total number of fatalities for the incident
- Description of event with keywords

The authors reviewed the detailed descriptions of each incident provided on each *OSHA 170 form* by inputting the inspection number provided in the OSHA dataset into the *OSHA Inspection Information* website (found at https://www.osha.gov/pls/imis/inspectionNr.html) to categorize each incident.

All OSHA-investigated construction fatality incidents in 2015-2019 were classified by Jenkins (2022) into one of the four major "Fatal Four" fatality categories. Each fatality was designated as either a *Fall*, *Struck-By*, *Caught-in/Between*, *Electrocution*, or *Other* by using information obtained from the *Fatality and Catastrophe Investigation Summaries* (OSHA 170 forms) produced during the OSHA investigations during this four-year time period. After the OSHA-investigated fatalities were categorized, each incident was individually sorted into one of 60 detailed fatality events based on the descriptions presented in the OSHA 170 forms. The study presented in this paper focuses on the nine of the sixty detailed events that were identified as *Electrocution* fatalities. The list of the nine detailed 'electrocution' events are shown in Table 1.

Table 1

Detailed events for electrical shock fatalities

Electrical shock by touching exposed wire
Electrical shock by arc to the ground
Electrical shock by ladder contacting power source
Electrical shock by scaffolding contacting power source
Electrical shock by crane/boom truck/drum truck contacting power source
Electrical shock by contacting power source while handing materials
Electrical shock from tool use
Shock/burn from flashback/lightning
Electrical shock, other/not specified

Study Results

As previously mentioned, there were 2,789 construction fatalities that were investigated by OSHA between the years 2015-2019. These investigated fatalities were categorized by Jenkins (2022) as either a *Fall* (41.5%, or 1,158 out of 2,789), *Struck-By* (15.4%, or 429 out of 2,789), *Caught-in/Between* (19.6%, or 546 out of 2,789), *Electrocution* (11.5%, or 316 out of 2,789), or as an *Other* (11.3%, or 340 out of 2,789) event based on the descriptive narrative provided in each of the *OSHA Form 170* inspection reports. This paper will focus on the OSHA investigation results for the 310 events responsible for 316 construction worker fatalities due to *Electrocutions* between 2015-2019.

Electrical Shock Fatalities

OSHA investigated 316 *Electrocution* fatalities that were distributed among 310 events between the years 2015-2019. 'Electrical Contractors' accounted for over thirty percent (31%, or 96 out of 310 events) of electrocution fatalities during this time period. A total of twenty-five different *North*

American Industry Classification System (NAICS) numbers for contractors experienced an electrocution fatality event according to OSHA's Inspection Reports. The top-5 affected contractors are shown in Table 2.

Table 2

Top-5 NAICS numbers for OSHA-inspected electrocutions, 2015-2019

NAICS Number	NAICS Description	No. of Fatality Events	Most Common Incident
238210	Electrical Contractors	96	Contact exposed wire
238130	Plumbing, Heating, and Air Conditioning	34	Contact exposed wire
237130	Power and Communications	32	Contact high-voltage line
238160	Roofing Contractors	30	Ladder contacting power
236118	Residential Remodelers	12	Contact exposed wire

These OSHA-investigated 'electrical shock' fatalities were sorted into nine different detailed events. The nine detailed 'electrical shock' events that resulted in construction worker fatalities between 2015-2019 are listed in Figure 2.

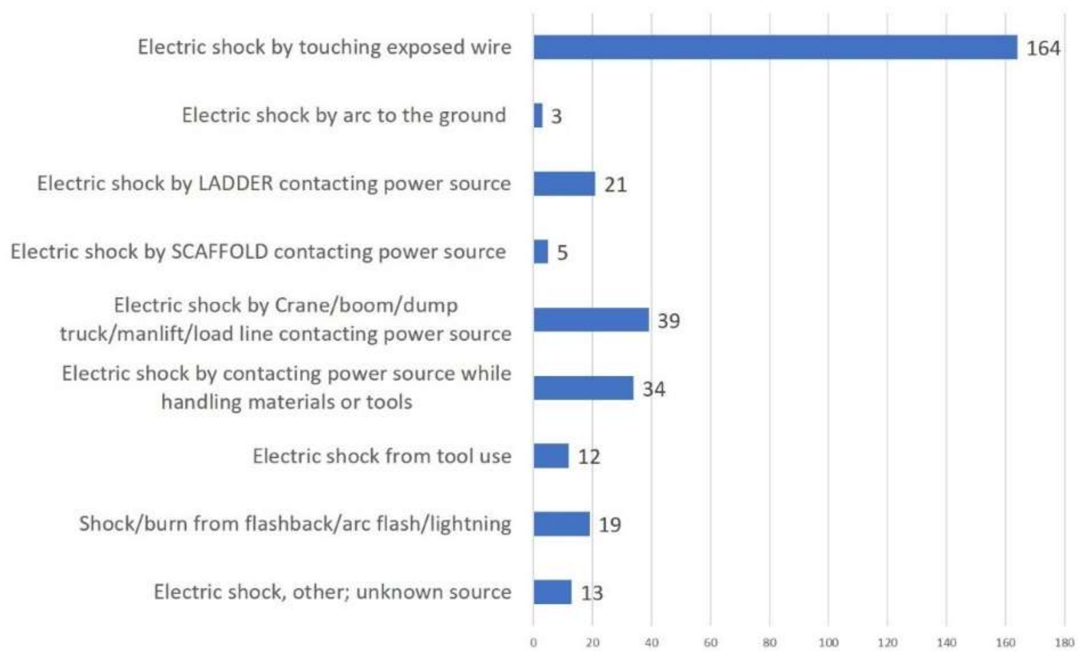

Figure 2. Construction electrocution events investigated by OSHA, 2015-2019

As shown in Figure 2, *electrical shock by touching exposed wire* accounted for the majority (52.9%, or 164 out of 310) of electrocution-related events in construction investigated by OSHA between 2015 and 2019. Working in *Close Proximity to Live Wire* was responsible for 68 (or 41.5%) of the

164 *Electric Shock by Exposed Wire* events, or 21.9% (68 out of 310) of the overall 'electrocution' fatalities.

Fatalities designated as *electrical shock by touching exposed wire* were also found to occur within areas designated as 'confined spaces' such as attics (8 events), crawl spaces (3 events), above-ceiling (2 event), and an equipment pit (1 event). Workers were also electrocuted by 'personally contacting buried utilities' (4 events).

There were also 18 fatal events due to *Equipment Installation* (*HVAC Equipment*, 10 events, *Other Equipment*, 8 events) and 10 events involving work on *Distribution Panels* in this category. *Personal Contact with Overhead Powerlines* added another 41 (or 25%) of the 164 *Electric Shock by Exposed Wire* events, which occurred when the workers were high enough to 'personally contact the overhead powerline'. These individual 41 events are included in the 132 'overhead powerline' events discussed in Figure 4 later in this paper.

The remaining 55 events (or 33.5%) related to 'touching exposed live wires' were work involving *Light Fixtures* (20), *Junction Boxes* (14), and *Transformers* (3). The distribution of events involving *Electric Shock by Touching Exposed Wire* is shown in Figure 3.

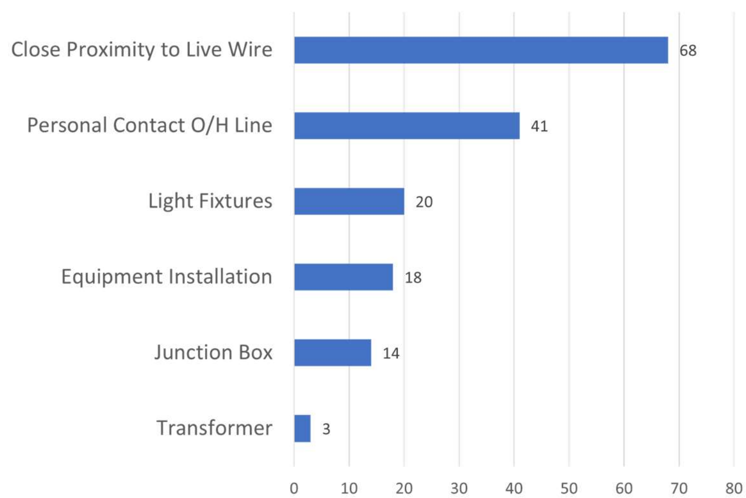

Figure 3. Distribution of electric shock by touching exposed wire events, 2015-2019

Overall, there were 132 (or 42.5%) of the 310 overall 'electrocution' fatal events that involved *contact with overhead powerlines* which were responsible for a total of 138 deaths. This number of events includes the 41 that were classified as *Personal Contact with Overhead Power Lines*. These personal contact events commonly occurred from *bucket trucks* and *aerial lifts*. Other ways workers came into contact (either directly or indirectly) with overhead powerlines included via *material, tools*, or *equipment*. The 132 sources (i.e. tasks and conditions) which caused workers to contact overhead electrical powerlines are identified in Figure 4.

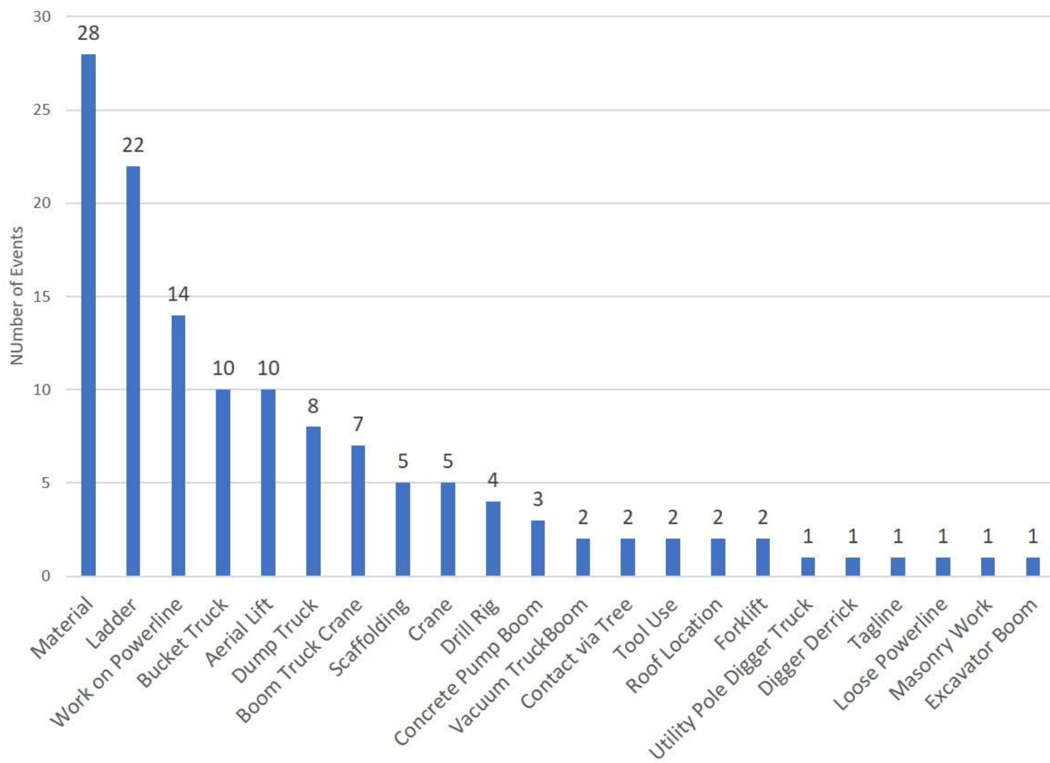

Figure 4. Sources of overhead powerline contact

Handling Materials accounted for the majority (28 out of 132, or 21,1%) of the *Overhead Powerline* incidents. 'Material' included structural steel elements (5 events, or 3.8%), extension poles for tools/bull floats (4 events, or 3%), aluminum street light pole/flag pole (4 events, or 3%), roofing materials/metal gutter/flashing (4 events, or 3%), and rebar (3 events, or 2.2%). The extension pole lengths involved in the fatal electrocution events were 6 feet, 10 feet, 23 feet and 29 feet in length. Workers used a variety of equipment to access their work and, unfortunately, get too close to overhead powerlines. This equipment included ladders (22 events, or 16.7%), bucket trucks (10 events, or 7.5%), aerial lifts (10 events, or 7.5%), and scaffolding (5 events, or 3.8%). Lengths of the metal extension ladders used in the electrocutions included lengths of 24 feet (one event), 32 feet (2 events), 35 feet (one event), 40 feet (six events), and 'no length given' for eight of the metal extension ladders. The remaining four ladder-related events included four aluminum shingle ladders used by roofers (one ladder at 35 feet and three ladders with no length given). Motorized equipment (dump truck, boom truck, crane, concrete pump, forklift, and excavator) used to haul or lift construction material accounted for 26 (or 19.6%) of the 132 electrocution fatality events.

Lastly, the *Electrocution* category accounted for five multiple fatality events in 2015-2019 resulting in 11 total fatalities. Therefore, it is important to note that safety incidents involving electrical shock have far reaching consequences. The descriptions of these multiple fatality events shown in Table 3 were taken directly from the OSHA Inspection Detail Reports.

Table 3

Construction electrocution multiple-fatality events investigated by OSHA, 2015-2019

Date	Fatality Event	No. of Fatalities
April 3, 2015	Employee #1 and Employee #2 were moving a **35-foot shingle ladder** to a different part of the roof of a residential house. As the employees moved the ladder, it came into contact with overhead power lines that were approximately 30 feet above the ground and 17 feet away from the dwelling. Employee #1 and Employee #2 were electrocuted.	2
September 28, 2015	Employees #1, #2 and #3 were operating an **excavator** when the boom of the excavator contacted the overhead power line. The power line broke and fell to the ground. The employees working near the falling power line were electrocuted. Employees #1 and #2 were killed. Employee #3 was hospitalized.	2
January 14, 2017	Employees #1, #2 and #3 were un loading and staging structural metal beams with a **boom truck crane**. The truck-mounted crane was unloading steel beams from an open top container when the boom truck cable touched an overhead high-power line causing electrical current to flow down the steel beam into the arms and bodies of Employees #1, #2 and #3, who were on the ground.	3
October 8, 2018	Employee #1 and Employee #2 were operating a **concrete pump truck** when the boom and hose touched the overhead power line carrying 13,000 volts. Employee #1 and Employee #2 were electrocuted.	2
July 24, 2019	Employees #1 and #2, employed by a construction company, were putting away the **35-foot aluminum extension ladder** they had used while painting the exterior of a house. The ladder contacted the house's overhead power service line, and electricity was conducted through the aluminum to the employees. Both Employee #1 and Employee #2 were electrocuted.	2

'Struck by Lightning" also contributed 14 of the OSHA-inspected construction worker fatalities between 2015-2019. All fourteen of these 'lightning' fatalitites involved workers being exposed outdoors during storm conditions. Seven (7 out of 14, or 50%) of these ligtning fatalities involved roofers being hit by lightning while on the roof.

Conclusion

The objective of this study was to examine electrocution-related construction fatalities investigated by OSHA between 2015-2019. Overall, OSHA investigated 310 'electrocution' events that were responsible for 316 construction worker fatalities between 2015-2019. The findings show that the majority of electrocution fatalities, unfortunately continue to happen as a result of coming into contact with exposed wires. Particularly when individuals are working around 'overhead powerlines', which led to 132 events resulting in 138 construction worker deaths. Similar studies have pointed to these types of events (Janicak, 2008; Zhao et al., 2014), yet the construction industry has failed to mitigate these preventable accidents. Some simple steps might help reduce or eliminate the exposure when working around overhead powerlines. For example, maintaining an adequate and safe working distancing from the hazard including knowing in advance the overall dimensions of the material and/or equipment required to complete the task. Also, using non-conductive ladders at all times, especially when working on or around electricity. These two sources of contact accounted for twice as many events/incidents than any of the other sources reported by OSHA.

References

Brown S., Harris, W., Brooks, R., Dong, X. (2021, February). Fatal injury trends in the construction industry. CPWR Center for Construction Research and Training. Accessed July 2, 2022. from https://www.cpwr.com/wp-content/uploads/DataBulletin-February-2021.pdf

Bureau of Labor Statistics news release (2020, December 16). Accessed July 2, 2022 from https://www.bls.gov/news.release/pdf/cfoi.pdf

CPWR – The Center for Construction Research and Training (2018, February). The construction chart book: The U.S. construction industry and its workers. 6th Ed. Assessed July 2, 2022 from https://www.cpwr.com/wp-content/uploads/publications/ The_6th_Edition_ Construction_ eChart_ Book.pdf

Janicak, C.A. (2008). Occupational fatalities due to electrocutions in the construction industry. *Journal of Safety Research*. 39, 617-621. Accessed July 2, 2022 from https://www.sciencedirect.com/science/article/pii/S0022437508001448

Jenkins, J.L. (2022). Analysis of U.S. construction" fatal four" fatalities investigated by OSHA in 2019. *Proceedings of the 58th Annual Associated Schools of Construction International Convention*, 28-36. Accessed October 28, 2022 from http://ascpro.ascweb.org/wp-content/uploads/2022/04/ASC2022_proceedings.pdf

Occupational Safety and Health Administration. (2011, April). Construction Focus Four Training. Accessed April 22, 2022 from https://www.osha.gov/training/outreach/construction/focus-four

Occupational Safety and Health Administration (2021). Construction industry. Accessed October 26, 2022 from https://www.osha.gov/construction

Zhao, D., Thabet, W., McCoy, A., and Kleiner, B. (2014). Electrical deaths in the U.S. construction [sic]: An analysis of fatality investigations. *International Journal of Injury Control and Safety Promotion.* 21:3, 278-288. Accessed Jul 2, 2022 from https://www.tandfonline.com/doi/full/10.1080/17457300.2013.824002

The Need for Commercialization of UAV for Building Façade Inspection

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Thirteen cities in USA are required to follow façade ordinance law for inspecting building façade. Traditionally the approaches to identify building façade defects are contact method with the help of monorail system, temporary suspended working platform and so forth. Visual inspections with contacted method suffer from several challenges and problems including low safety, low productivity, and low reliability. The results of visual inspection can be reliable when dealing with small structures with easily visible parts, but it is not easy for a surveyor to analyze high rise buildings or assess anomalies that are in deeper location without proper means of access and with unfavorable weather conditions. Visible inspection highly depends on the experience of the surveyor alone making the process subjective, human dependent, time consuming and having low accuracy in defect's measurement in certain situations. It is important to adopt a standard building façade inspection strategy which is fundamental throughout the life cycle analysis of the building. Unmanned Aerial Vehicle (UAV) coupled with good quality cameras to capture HD images and videos or infrared cameras and 3D laser scanners to identify damages and cracking in building facades is promising technology which should be commercialized to inspect building facades.

Keywords: UAV, building façade inspection, façade ordinance law

Introduction and Literature Review

Building façade refers to the face of the building or exterior of the building. Façade is a complex system to design, build and maintain, therefore there is a need of technological advancement in this department. Humidity is one of the main causes of façade anomalies but loads, stress, radiation, pollution, leakage, salts, molds, bacteria, insects, birds etc. may also significantly affect the façade's performance. Elements of building façade can fall off and cause threat to objects and people below if they are not maintained and inspected regularly. 51-year-old Nelson Salinas was found lying unconscious and unresponsive on a scaffold after suffering trauma from his head. 39-year-old Oumar Ba was walking down St. Johns Place in New York when debris and bricks fell from above on top of him. Erica Tishman died in New York city in late 2019 after being struck by a piece of falling façade from 105-year-old high rise in Manhattan. These are few among many façade fall related fatality that could have been avoided. The scope of façade inspection includes all the exterior surface including all the exterior features attached to the building, parts of building located on or near the exterior and externally mounted equipment (Guidelines on Periodic Façade Inspection, 2022) Inspection Practice includes visual inspection by a competent person. The surfaced defects detected during inspection are documented by photos or sketches (Michael Y L. Chew et al., 2022). Building façade inspection involvers three major steps: planning, engineering analysis and execution and execution. Execution is the actual conduct of inspection (J. Mohammad, 2021). Execution of Inspection requires supervision by a licensed architect, structural engineer, or registered professional engineer. Building Façade Inspection can be Visual Inspection and Detailed (Visual and Hands-On Inspection). Most of the inspections are done visually by experienced professional with the help of visual aid equipment such as binoculars, cameras, flashlight, video camera with lens mounted at an extended flexible line for observing hard-to-reach areas, magnifying glass for hard-to-detect cracks, etc. Visual Inspection with contact method (Detailed Inspection) uses visual aid equipment and touching the surface by hands-on pushing, pulling, and probing to locate loose and degraded material and sounding to locate areas of delamination and future spalls (J Mohammad et al., 2022). Hands-on Inspection or contact inspection requires lot of time and manpower. One must ensure the skill of the façade inspectors along with their safety. They must ensure that the rope being used for surface access is properly hooked, the harness is in good condition, all the inspectors are provided with helmets and safety jackets, and they are wearing proper construction site-approved shoes. Therefore, the use of this methodology often meets with difficulties. It is hard to inspect the faces of building facade that are difficult to access, involves security risk for inspectors, poses safety risk for inspectors, and causes infeasibility for inspection of urgent nature due to high cost and unnecessary means involved in the inspection. (C Zhang et al., 2022). In the turbulent world of emerging technologies, it is very important to understand the relationship between user needs, existing solutions, and what new technology can bring to the table. This paper aims to understand if or not UAV is answer to the needs of modern complex façade inspections that requires higher accuracy and efficiency.

Façade Ordinance

Façade ordinance is a law passed by local authorities for periodic inspection of building facade to ensure public safety. The following table provides information on façade ordinance in 13 of cities in United States. Third column as written in the table (see table 1) provides information on Visual and hands on inspection requirement for each city. This column tries to highlight the potential market for usage of UAV for general visual and detailed visual inspection of building facades. Title 14 CFR Part 107 remote Pilot Small Unmanned Aircraft Systems Airman Certification is required for Drone usage.

Table 1: Façade Ordinance Requirements for different cities

City	Requirement for Inspection	Visual Inspection and Hands on Inspection
Boston, Massachusetts	Interval: every 5 years; Greater than 70’ in height or 35,000 cu ft	Buildings in category 79’-125’ tall requires only Visual Inspection.
Chicago, Illinois	Interval: every 4,8, or 12 depending on the category; Greater than 80’ in height or taller	Buildings for Short form program requires only Visual Inspection
Cincinnati, Ohio	Interval: every 8 or 12 years; Greater than 5 story height or more than 15 years old	Remote inspection allowed in place of hands-on inspection or to faces of façade that are more than 25’ from areas accessible to public

Cleveland, Ohio	Interval: every 5 years; Greater than 30 years old and 5 stories or 75’ tall	Visual Inspection required from less than 6’ along with hands-on inspection
Columbus, Ohio	Interval: every 5 years; Greater than 20 years old and located within 10’ of a public right-of-way	Both Visual and Hands-on Inspection required
Detroit, Michigan	Interval: every 5years; Greater than 5 stories	Only Visual at distances greater than 6 ft and detailed (visual and hands-on) at distances less 6 ft inspection.
Milwaukee, Wisconsin	Interval: every 5 and 12 years based on building category; Greater than 5 or more stories and more than 15 years old	Visual remote examination for façade that cannot be examined through close visual examination
New York, New York	Interval: every 5 years; Greater than 6 or more stories, including basements	Approximately 25% of building façade requires hands on inspection while other 75% can be inspected visually
Philadelphia, Pennsylvania	Interval: every 5 years 6 or more stories in height or buildings with appurtenances more than 60’ in height	Visual remote examination for façade that cannot be examined through range examination
Pittsburgh, Pennsylvania	Interval:1 year of adoption of code and successive inspection every fifth year of date of original inspection; all buildings except group R3	Visual remote examination for façade that cannot be examined through close-range examination
Saint Louis, Missouri	Interval: every 5 years; Greater than 6 stories	Visual remote examination for façade that cannot be examined through close-range examination
San Francisco, California	Interval: 10 years after initial inspection; Greater than 5 stories	Visual remote examination for façade that cannot be examined through close-range examination

All remote inspections can be done visually but not all visual inspections are remote. Visual inspections can be done remotely with advanced UAV technologies. For faces of façade that can be inspected remotely drone technology is a very good option. Facades that require only visual inspection UAVs can be used to access façade faces in challenging spots. For faces of façade that requires both visual and hands-on inspection drones can be utilized detect anomalies identified during the general inspection in difficult to reach parts of the façade.

Building Façade Defect Zone Classification

During the lifecycle of building operation defects and damages accumulate in the structure façade. Defects such as destruction of concrete protective layer, exposure of reinforcement, destruction of concrete of carnal slabs, absence of glazing on windows, destruction of wall panels, falling off plaster, molding, corrosion of fire ladders etc. occurs commonly if facades are not maintained properly. The building façade defects zone can be identified into five characteristic zones (T A Krahmalny et al., 2019). Defects can be in form of soaking, molding, corrosion, or distortion. These defects can lead to falling of concrete pieces from a height causing danger to the people and objects nearby.

Figure 1: Residential buildings in Brooklyn with building façade defects

Sidewalk Shed Erection

Sidewalk shed should be erected below the buildings which have been issued notice for façade inspection or buildings which have been deemed unsafe by the authority. Figure below (see fig 2) shows a five plus story tall building, in the 38th street, Queens, NY which was issued a notice for façade inspection. The sidewalk shed was constructed for safety of pedestrians and will remain until the building is deemed safe.

Figure 2: Different phases of sidewalk shed erection

Façade Inspection Report

Façade Inspection Report refers to the report prepared by licensed engineer, architect, or qualified personnel. It is prepared after the inspection has been completed. The report provides information on whether the building is safe or unsafe or if it needs repair. The report was acquired from a firm that was doing façade restoration work in a building with unsafe façade faces. Figure 3 (see below) is a snippet of façade inspection report out of 50 pages which were acquired from a façade inspecting firm. In façade inspection reports, defect is captured with help of camera, is highlighted, in the picture and the condition of the defect is explained. The inspection report ends with a table where pictures of defect with specific assigned numbers are tabulated, and recommendation type is assigned. The recommendation type can be to remove, to replace or to repair. Every façade inspector is required to use ASTM E 2270 Standard Practice for Periodic Inspection of Building Facades. Façade defects should be highlighted in the picture when report is prepared, and condition of the defect should be made clear as per the façade ordinance of the city.

Figure 3: Pictures of building façade defects as shown in pages of façade inspection report

Research Goals and Methodology

The goal of this study is to prepare survey data on the need for the Commercialization of UAVs for Building Façade Inspection. It aims to establish why building façade inspection is important and present interview results of professionals who have experience with Building Façade Inspection procedures, their opinions, and feedback on usage of UAV for building façade inspection.

Method of this study has three phases: content generation, data collection and assessment & evaluation. Phase 1 (content generation) aims to create set of questionnaires to interview professionals who have experience with Building Façade Inspection. The questionnaire will be curated to show the current trend in building façade inspection, their challenges and gauge if UAV is the answer to those challenges. For this research three questions were prepared. Phase 2 (data collection) aims to collect data by means of interviews and/or google forms prepared with the set of questionnaires. Phase 3 (assessment & evaluation) aims to conclude the data from phase 2.

Results and Discussion

178 people were interviewed for the purpose for this research. 95% of the responses were through the interview process and 5% were through the responses recorded through the distribution of google forms. Most data were collected through interviews because interviews provided access to ask follow-up questions and to go in-depth regarding the subject. The sources of the interviewee have been described below:

1) NYC DOB build safe, live safe Networking Event

Around 12 people were interviewed during this event which happened on July 29th, 2022.

2) Chicago Build Expo 2022

18 people were interviewed during the two-day expo from Oct 13 – Oct 14, 2022.

3) LinkedIn

6 responses were collected from the google link distributed to building façade inspectors in LinkedIn

4) Cold Calling and Email

142 interviews were conducted via cold calling and emailing AEC (Architectural, Engineering and Consulting) firms, building owners and engineers who have experiences with building façade inspection. Among which 105 were conducted during the process of National Science Foundation Innovation Corps (NSF I Corps) cohort program in costumer discovery phase.

The interviewee comprised building architects, engineers, project managers, designers, estimators, building owners, licensed building inspectors, facility managers, and others. Others include superintendents, licensed safety personnel, restoration workers, and people who have been in construction for one or more years. Most of the interviewees were employees of an architectural firm, a contracting firm, or an engineering firm, or were working in the building inspection department or local authorities. Three questions asked during the interviews were:

• “What are the challenges faced during building façade inspection with the conventional procedure?”

• “Do you think UAVs can address the challenges faced during façade inspection? If yes, could you name some of the challenges that could be addressed by the usage of UAVs?”

• “Do you feel comfortable in adopting UAVs for façade defect detection?”

For the first two questions, only service providers (104) were interviewed as it involves one to have experience in conducting façade defect detection to answer the question. For the last question, both service providers (104) and clients who receive building façade inspection services (74) were interviewed (178).

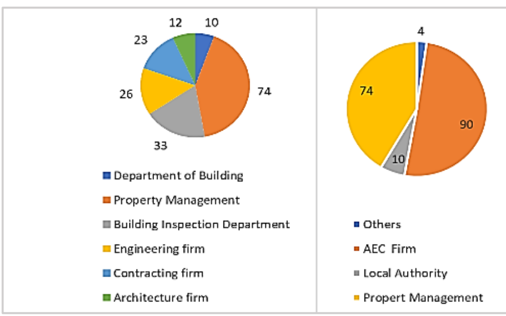

Figure 4: Demographic of Interviewee

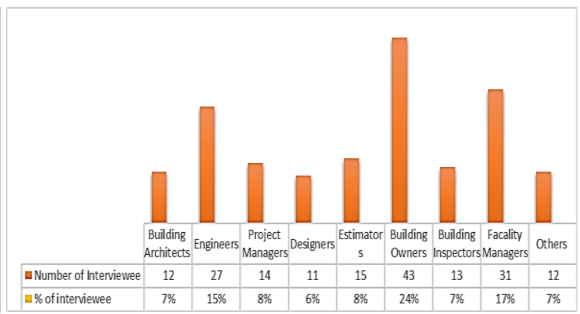

Figure 5: Interviewee Designation

Interview Results on Challenges Faced during Building Inspection

For the first part of this interview, the interviewees (104 service providers) were asked to name some challenges faced while doing building façade inspection with conventional procedure. Interviewees were asked to name top five challenges faced with conventional procedure. List of challenges and number of interviewees who named these challenges as their top five has been tabulated below.

Table 2: List of challenges and the number of interviewees who named them.

Challenges with conventional procedure	% Of Interviewee who named them
Time Consuming	96%
Unable to inspect blind Spots of Building façade	100%
Danger of fall while in a monorail system or hanging through rope	86.5%
Challenging to inspect facade complex structure	100%
Errors in defect detection	85%
Unable to cover 100% of façade area manually	100%
Errors in report generation	96%
Lack of awareness regarding building façade maintenance	92%

Top three challenges which were named the most by interviewees is described below along with quoted sentences. Quoted sentences written below are some parts of the sentences spoken during the interview conversation which might not have the exact same wordings but aims to express the same meaning. Most of the data collected were from interviews done via audio or video call.

1) Manual Inspection is not able to cover 100% of the façade area of the building

As quoted from one of the service providers of facade inspection "It is not possible to cover 100% of the façade area especially if the building is in highly populated area and there is a narrow gap. Even in such cases we try to inspect those faces by employing advanced assess equipment but even then, sometimes we are not able to cover 100% of the area". Many agree that even though manual inspection is most widely used technique automated inspection if done correctly will hold same if not higher accuracy. "UAV should be used and must be used to aid building facade inspection especially of high-rise structures" says one of the engineers from EDG Firm in New York.

2) Danger of life while accessing height of building façade for inspection.

It is very challenging to inspect façade with complex structure without advance technological support. Façade access equipment that are used for manual inspection to access height will always pose danger to life. Some of the building façade access equipment are: Bosun's chair, Building Maintenance Unit (BMU), Davit etc. "There is always danger to fall" says one of the interviewees. "There have been cases where scaffolding, trench and access equipment has collapsed. So, there is always a risk when manual inspection is opted" says project manager who works in Technico Construction, New York.

3) Unable to detect blind spots of building façade

Blind spots of a building structure often remain undetected while manual inspection if advanced technologies are not used. Many interviewees agree that there is lack of awareness among people regarding the importance of building façade inspection. According to the service providers "Many clients when they come with the request to get their building inspected would only get the building inspected if law requires them to or if their building is deemed inhabitable by local authority of the city. There are very few building owners who come for building inspection services for their personal assurance. Therefore, it is important that the building owners must be made aware of the dangers to risk of life posed by damaged building facades". This is a quoted interview provided by one of the service providers in New York City.

Interview Results on Usage of UAV For Building Façade Defect Detection

The data shows results of 104 interviewees who were service providers. The question asked was "Do you think UAV can address the challenges faced during façade inspection? If yes, could you name some of the challenges that you believe UAV can address?". All the interviewees agreed that UAV can be used to address the challenges in building façade inspection. 100% the interviewees who were service providers agree that UAV can be used to:

- Investigate blind spots in the building façade area
- Cover more façade area for inspection for increased accuracy
- Inspect building façade remotely
- Minimizing the risk of fall when hanging through rope system for inspection
- Cut cost in equipment's needed for laborious manual inspection
- Aid Human inspection for more accuracy

Interview Results for UAV adoption choices for Building façade Detection

Four options were given to interviewees as shown in the table (see table 3). They were asked to choose one of four. The interview results showed that most of the interviewees are comfortable adopting UAV to aid human inspection rather than using it remotely for fully automated inspection. This result was very understandable because using UAV remotely is still a very new technology. 27 of the interviewees who were all service providers said that they are comfortable in adopting fully automated remote inspection if law allows. 41 interviewees who were mix of clients and service providers were comfortable in using UAV only for inaccessible locations. 102 interviewees among which 92 were service providers were comfortable in adopting UAV to aid human inspection. 8 interviewees who were facility managers were comfortable with the existing technologies because they were unsure if the new technology bears same accuracy as the conventional one. 100% of the interviewee who were service providers were open to adopting UAV for building façade inspection if law would allow. 8 interviewees were not comfortable in adopting UAV for façade inspection and they were all clients. The clients who were not comfortable said so because they feel manual inspections bears more accuracy.

Table 3: Data for different UAV techniques interviewees are comfortable adopting

UAV adoption choices		**Number of Interviewee who named them**
1	Usage of UAV for fully automated remote inspection	27
2	Usage of UAV for inaccessible location	41
3	Usage of UAV to aid manual inspection for increased accuracy and efficiency	102
4	Usage of Conventional Manual inspection techniques without UAV	8
	Total	178

Conclusions and Future Research

Interviewees agree that having UAV for façade inspection: reduced the cost of building inspections, shortened the duration of building inspections, and provided more area coverage than manual inspection in a shorter time. The data shows that the building industry is very much willing to utilize UAVs. The results show that there is an inability to cover 100% of the façade area manually, unable to detect blind spots, and the risk of falls are the top three challenges of conventional inspection. Interviewees agree that these challenges can be addressed if UAVs are used. The other challenge is the safety of building inspectors who must hang via monorail along the façade surface for inspection which includes a range of hazards such as falling off, exposure to bacterial hazards, fungal hazards, or even physical attack by violent occupants. From the survey results gathered from this research, it is found that about 15% of the interviewee were comfortable with the idea of adopting UAVs to replace human inspection. About 23% were comfortable with using UAVs for inaccessible locations and about 57% were comfortable with adopting UAVs to aid human inspection. There were around 4% of the interviewees were not comfortable with adopting UAV for the façade inspection because they did not have much knowledge about it.
It was identified that the danger of collision of UAVs with pedestrian and nearby buildings will be reduced significantly if drone-based inspection were to have an automated optimized path. Optimized UAV path that can detect obstacle should be studied for future research.

References

ASTM E2270, *Standard Practice for Periodic Inspection of Building Facades for Unsafe Conditions* (2019). Accessed August 7, 2022, from https://www.astm.org

Boston. 2019. *City of Boston municipal code.* Boston: City of Boston.

Chicago. 2016. *Rules regarding the maintenance of high-rise exteriors walls and exterior enclosures.* Chicago: City of Chicago.

Cincinnati. 2020. *City of Cincinnati code of ordinances*. Cincinnati: City of Cincinnati.

Cleveland. 2020. *City of Cleveland code of ordinances*. Cleveland: City of Cleveland.

Columbus. 2020. *City of Columbus code of ordinances*. Columbus, OH: City of Columbus.

Detroit. 2017. *City of Detroit code of ordinances*. Detroit: City of Detroit.

IBC (International Building Code). 2009. *International building code*. Country Club Hills, IL: International Code Council.

Milwaukee. 2001. *City of Milwaukee City charter and code of ordinances.* Milwaukee: City of Milwaukee.

New York. 1998. Local Law 11 of 1998, *periodic inspection of the exterior walls and appurtenances of buildings greater than six stories in height.*

New York: City of New York. New York. 2011. Promulgation details for 1 RCNY 103-04. New York: City of New York.

Phila. 2010. *The Philadelphia property maintenance code of the Philadelphia building construction and occupancy code*. Philadelphia: City of Philadelphia.

Pittsburgh. 2020. *Code of ordinances*. Chapter 1004: *International property maintenance code adoption*. Pittsburgh: City of Pittsburgh

SF (San Francisco). 2016. *City of San Francisco building code*. San Francisco: City of San Francisco.

SL (City of Saint Louis). 2010. *Ordinance 68788, An Ordinance adopting the International Building Code. St. Louis*: City of Saint Louis.

T. A. Krahmalny, S. Evtushenko (2019) *Typical defects and damage to the industrial buildings' facades*, IOP Conference Series: Materials Science and Engineering, Volume 775, International Conference on Civil, Architectural and Environmental Sciences and Technologies (CAEST 2019)

Dias, I.S.; Flores-Colen, I.; Silva, A. *Critical Analysis about Emerging Technologies for Building's Façade Inspection. Buildings* 2021, 11, 53. https://doi.org/10.3390/buildings11020053

Muqing Cao et al., (2020) *Online Trajectory Correction and Tracking for Facade Inspection Using Autonomous UAV*, Engineering 2020 IEEE 16th International Conference on Control & Automation

Construction worker from Queens killed by falling stone on East Side (2019), Accessed October 5, 2022, from https://www.nydailynews.com

Brooklyn Building's Facade Collapses On Sidewalk, Crushes Man Walking By (2020), Accessed October 5 2022, from https://www.nbcnewyork.com

Jamshid Mohammadi, (2021) *Building Facade Inspection Process: Administration and Management Matters*, Accessed on October 26 2022, downloaded from asce.library.org by Marquette University Libraries

Erica Tishman death: Building owners knew of facade issue for over a year (2019), Accessed October 2022, from https://nypost.com

Guidelines on Periodic Façade Inspection, 2022, Accessed September 7 2022, from https://www1.bca.gov.sg

Jamshid Mohammadi, A. Longinow, D. K. Johnson and N.R. Iwankiw (2022) *Nondestructive Evaluation and Monitoring Methods for Facade Inspection and Conditions Assessment*, Practice Periodical on Structural Design and Construction, Accessed on October 12, 2022, from https://www.asce.org

C Zhang, Y Zou1 and J Dimyadi (2022), *Integrating UAV and BIM for automated visual building inspection: a systematic review and conceptual framework,* World Building Congress, 2022, IOP Conf. Series: Earth and Environmental Science

Summary Sheet

We thank all three reviewers for their valuable comments and suggestions that helped make this paper better. Based on the three reviews, we have made the following changes to the paper to address the reviewers' comments/suggestions:

---------------------- REVIEW 1 ---------------------

Thank you very much for your comments and suggestions! We agree to all the comments and suggestions and have made the following modifications: (1) Removed possessive pronouns; (2) changed cubic meter to cubic meters and addressed the typo of "United States."; (3) added brief explanation of the presented results in the abstract; (4) added a figure (Figure 1) to summarize EE and EW data reported in literature; (5) rephrased the vague/broad sentences or added text to make them clearer; (6) added more explanation in research methods section to describe how monetary data was converted into energy and water units; (7) added brief text to the conclusions section to elaborate the educational aspects. Note that we have submitted this paper to the Sustainability & Energy Efficiency in the Built Environment Track.

---------------------- REVIEW 2 ---------------------

Thank you so much for your comments and review! We have made the following revisions to address your comments: (1) spell checked the document; (2) we have removed the use of "we"; (3) we have reduced self-citations (rational of the three studies that are self-cited is provided in the next paragraph); (4) modified the title and abstract to reflect and indicate the case study aspect; (5) regarding the gap from previous studies, previous studies did not quantify the energy-related water use as mentioned in the sentence "Even though most of these studies quantified both direct and indirect EW of buildings, the energy related EW (EREW) was not evaluated (Hong et al., 2019)." The last paragraph of the introduction section further discusses what is the contribution of this paper; (6) added Figure 1 to summarize the EE and EW results of some previous studies; (7) checked all references to make sure all cited studies have been included in the reference list; (8) Figure 1 was confusing. Thank you for pointing this out! We have removed the figure and replaced it with a table that lists the values per unit area; (9) the cost data table can be provided but it would further increase the number of pages. Table 1 provides the share of the total cost each building element has. We have now included the total construction cost in the text to give a reader an idea about the cost of each element/service based on the mentioned %; (10) we have added more text in the methodology to make it clearer; (11) we have included the results of the regression analysis including the *significance of F* and the *p-value* and have added text to clarify this. We have also included references to justify why $r^2=0.66$ may indicate a strong positive correlation; (12) more text has been added to the conclusions section to clarify why multi-objective optimization genetic algorithm (MOGA) is relevant and to explain how designers can use this information to make decisions.

Rationale for self-citation: We have just used three studies that are self-cited. Venktaraj & Dixit (2021) is used to make recent assertions about embodied energy flows that may not be made by citing other studies. Dixit et al (2022) and Dixit and Singh (2018) were used to indicate that more detailed information about the development of the IOH-based EW and EE macroeconomic models can be found here, respectively.

---------------------- REVIEW 3 ---------------------

Thank you for your valuable comments and suggestions! We have done the following revisions/responses to your comments: (1) because we sourced the data from the schedule of values, we do not have the material quantity information. We, instead, provided the cost of each material per unit of building area in Table 1 to give a reader a better idea; (2) we have added some more information about the case study building. However, since we are not allowed to share details such as the name, picture, floor plan of the building, we have to honor the confidentiality. I would kindly urge the reviewer to consider this aspect; (3) the material costs only include the material used in the construction of building excluding the building services/systems. We have added some text to clarify this in the paper.

Measuring Embodied Energy, Carbon, and Embodied Water of Construction Materials: A Case Study of University Building

Name 1 and Name 2

University Name
City, State

Buildings consume nearly 40% of global energy supply and 16% of fresh water each year in their construction and operation, which consequently results in 39% of the global carbon emissions. Looking at the rate at which the global climate is changing and the frequency and severity of droughts, wildfires, and extreme heat events across the globe, reducing not just energy and carbon impacts but also water use associated with building construction is essential. This paper presents two input-output-based hybrid (IOH) models to compute and analyze the embodied energy (EE), embodied carbon (EC), and embodied water (EW) of fourteen commonly used construction materials and a university building as a case study. The results indicate that the total EE, EC, and EW values of the case study building are 4.5 MBtu/ ft^2, 528.7 $kgCO_2/ft^2$, and 1,049.6 gallon/ft^2, respectively. These results emphasize the extensive energy, carbon, and water impacts associated with building construction, which must be addressed. Furthermore, the intensities of total EE and EW of the construction materials vary in the range of 0.1-11.0 MBtu/ft^2 and 2.2-134.3 gallon/ft^2 indicating the importance of water use as an important indicator for material selection. The calculated values of EC and EW share a strong positive correlation at the building level, which weakens when analyzed at the material intensity level. Findings highlight the significance of selecting construction materials based on not just energy and carbon impacts but also embodied water use.

Key Words: Embodied energy, embodied carbon, embodied water, life cycle energy, buildings

Introduction

Construction materials and construction projects can play a pivotal role in reducing the energy and environmental impacts of the globe since buildings alone are responsible for over 40% of global annual energy use and nearly 40% of global carbon emissions (Nizam et al., 2018; Rasmussen et al., 2018; Venkatraj & Dixit, 2021). Although most of this energy use is due to operational energy consumption in air conditioning, heating, and lighting buildings and powering building equipment, embodied energy may share a significant portion of this energy consumption (Azari & Abbasabadi, 2018; Dascalaki et al., 2021). Embodied energy accrues over a building's life cycle due to the use of construction materials and processes with transportation (Crawford and Treloar, 2005). It includes all direct energy consumed in all onsite and offsite construction, installation, and transportation processes and energy used indirectly by using construction materials, which consume considerable energy is their manufacturing (Taffese & Abegaz, 2019). This energy footprint of buildings may get much larger if a more complete assessment of embodied energy is included. There are three approaches to measure embodied energy of a building (Nizam et al., 2018; Azari & Abbasabadi, 2018): (1) process-based; (2) input-output-based and (3) hybrid. In a process-based method actual energy use data is collected from material manufactures and construction sites, whereas the national level monetary transactions between industry sectors are converted into energy flows in an IO-based technique to compute embodied. Consequently, process-based calculations are regarded as reliable but incomplete since not all energy inputs may be collected due to data confidentiality and unavailability energy (Nizam et al., 2018). On the other hand, IO-based energy results are considered complete because the IO system covers all inter-industry transactions. However, since monetary data is converted into energy inputs that requires energy process, IO calculations are plagued by fluctuations in energy and material prices as well as the assumptions of proportionality and homogeneity inherent in the IO system (Chang et al., 2014; Venkatraj & Dixit, 2021). Hybrid approach integrates the two methods to offer embodied energy calculations that are complete as well as reliable (Crawford and Treloar, 2005). One of the hybrid methods is input-out-based hybrid (IOH) technique that has the potential to offer enhanced completeness, specificity, and reliability of calculation (Crawford and Treloar, 2005).

In an IOH method, IO data is utilized to compute a direct requirement matrix that represents the inputs ($) of different commodities required to produce one $ worth of a particular commodity (Dixit et al., 2022). Using Leontief's Inverse matrix technique, the direct requirement matrix is converted into a total requirement matrix that lists total inputs of commodities needed to generate one $ output of a commodity. The total requirements represent the direct and indirect inputs needed for the production of a commodity. Eventually, direct and indirect embodied energy (EE) intensities are calculated for commodities (e.g., cement, steel, wood) by totaling their input of energy commodities (coal, natural gas, electricity) (Dixit and Singh, 2018). In addition to embodied energy, buildings and construction materials must also be analyzed for their carbon emission impacts since materials may have the same embodied energy but differing carbon emissions. Because each material is manufactured using different types of energy sources, its carbon dioxide emissions may be quite different from other materials (Hu, 2020; Hendriks et al., 1999).

Buildings also consume over 16% of global fresh water in their construction (Nizam et al., 2018; Rasmussen et al., 2018). Because fresh water availability is being threatened due to increased severity and occurrences of wildfire, extreme heat, and drought conditions, analyzing how much water is depleted by construction materials is essential to understand if a material is energy efficient and carbon neutral, is it also water efficient (Chen et al., 2019). Like, EE, each building and its constituent materials also have embodied water (EW) use that must be assessed and applied to design decisions such as material selection (Dixit et al., 2022). EW of a building is also comprised of a direct and an indirect EW component, which represent the fresh water used directly in construction processes and indirectly by using construction materials, respectively (Pullen et al.,2012; Mousavi et al., 2015; Bardhan and Choudhuri, 2016). Onsite construction operations may utilize between 0.5 and 7.5 kiloliters (kL) of water on a typical construction project (Choudhury and Roy, 2015; Choudhuri, 2015; Crawford and Treloar, 2005). However, these values of water use may vary depending on the size, type, location of the construction project. Construction materials also deplete water in their raw material production, processing, transportation, and production, which must be covered under the indirect EW component. Materials such as structural steel may consume 0.6-2.6 cubic meters of water in each ton of their production (Strezov et al., 2013). Concrete, a material used in commercial buildings in bulk quantities, may deplete up to 180 liters of fresh water in each cubic meter of its production (Mellor, 2017). In addition to the direct and indirect EW, water may also be consumed indirectly by using different energy sources. Each energy source (e.g., natural gas, coal, electricity) used as embodied energy (EE) uses fresh water in its production and delivery, which must be considered as energy related embodied water (EREW). For instance, nearly 40% of water is drawn by thermos-electric power plants in the United States to produce electrical power (Wu & Chan, 2017). To produce one MWh of electricity, roughly 78 cubic meters of water is depleted by coal-fired power plants in Australia (Strezov et al., 2013). Primary energy sources such as coal, petroleum, and natural gas consumed roughly 0.37, 0.06, 0.03 cubic meters of water per GJ of energy produced (Grubert & Sanders, 2018). Surprisingly, renewable energy-based electricity production through concentrated solar power (CSP) has one of the largest water footprints (4.7 liter/kWh) for producing electrical power (Li et al., 2012).

Multiple studies have evaluated EE, EC, and EW of buildings using different methods. In particular, Collinge et al. (2013), Krogmann et al. (2008), and Sharma et al. (2012), calculated and analyzed the EE of educational buildings and reported 5.1, 6.3, and 18 GJ/m^2 of EE use, respectively. Dixit and Singh (2018) applied an IO-based hybrid approach to compute the EE of higher educational buildings in the range of 30.6 and 50.1 GJ/m^2. Recently, Venkatraj and Dixit (2021) compared the EE of a renovated and a new construction building and reported 18.8 GJ/m^2 and 6.1 GJ/m^2 of EE, respectively. Studies by Treloar and Crawford (2004), McCormack et al. (2007), Bardhan (2011), and Bardhan and Choudhury (2016) computed EW of various commercial and residential buildings as roughly 54.1 kiloliters/m^2, 201. kiloliters/m^2, 27.0 kiloliters/m^2, and 19.4 kiloliters/m^2, respectively. In existing EW studies, the indirect EW was found to contribute to roughly 61-93% of the total EW of buildings, further highlighting the importance of construction material selection for lower EE, EC, and EW impacts (Dixit et al., 2022). Even though most of these studies quantified both direct and indirect EW of buildings, the energy related EW (EREW) was not evaluated (Hong et al., 2019). Figure 1 summarizes the EE and EW results of some previous studies.

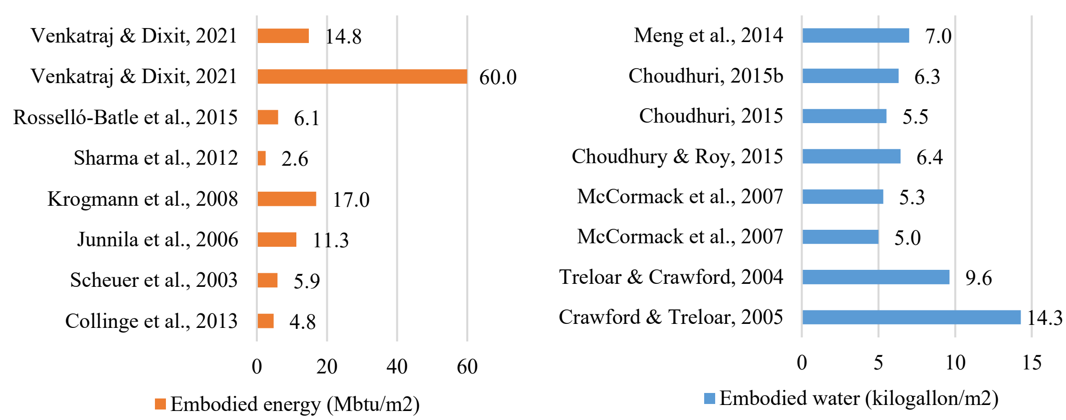

Figure 1. Summary of EE and EW values reported in the literature

Although several studies have quantified and analyzed EE and EW of buildings, research on construction materials' environmental impacts in terms of EE, EC, and EW remains limited. In this paper, two IOH models are presented to compute and analyze the amount of energy, carbon, and water embodied in construction materials. The aim is to underscore the significance of choosing construction materials that reduce not just EE and EC but also EW of buildings.

Research Methods

The main goal of this paper is to offer an understanding of how different construction materials differ in terms of their carbon and water footprints and how this may create environmental impact tradeoffs in design decisions geared towards improving environmental sustainability of buildings. Two research objectives are pursued:

- Develop IOH models using latest IO data of the United States economy to calculate embodied carbon (EC) and embodied water (EW) of construction materials
- Analyze the calculated values of EC and EW of construction materials for potential interdependencies to highlight the significance of reducing not just carbon emission but also water use

Development of macroeconomic IOH models

Macroeconomic models to compute embodied carbon and water use are developed in three steps. In the first step, latest benchmark IO data was collected from the United States Bureau of Economic Analysis (USBEA). IO data is offered in raw *Make* and *Use* tables. The *Make* table (industry-by-commodity 405 x 401 matrix) shows how commodities are manufactured by each industry sectors. The *Use* table (commodity-by-industry 401 x 405 matrix) lists the inputs of commodities required by each industry sector to produce their one unit of output. By adjusting the *Make* table for industry scrap and calculating the *Market Share* matrix, a commodity-by-commodity direct requirement matrix was computed that gives the monetary inputs of each commodity to manufacture one dollar worth of a particular commodity. More details of the calculations can be found in Dixit and Singh (2018) and Dixit et al. (2022). Finally, using the Leontief's Inverse matrix approach, a commodity-by-commodity total requirement matrix was created that showed the amount of a commodity (in dollars) to produce one dollar output of each commodity. The total requirements listed direct as well as indirect requirements. For instance, in the case of cement production, direct requirements cover all direct inputs such as, limestone, slate, clay, slag, and gypsum required by a cement plant to produce cement. the indirect requirements, on the other hand, indicate the inputs required to produce the direct inputs.

The total requirement matrix shows the amount of energy commodities and water commodities consumed by other commodities such as those representing construction materials in producing their one dollar of output. However, these energy and water inputs are in monetary units ($), which must be converted into physical energy (MBtu) and water use (gallons) units by acquiring sector-specific energy and water prices. Since prices of utilities fluctuate significantly, embedding energy use and water use data into the IO model in physical units is essential to avoid using energy prices. In the second step, the amount of energy and water consumed by industry sectors of the United States economy was collected by referring to federal sources such as, the United States Department of Agriculture (USDA), United States Department of Energy (USDOE), United States Census Bureau (USCB) and United States Geological Survey (USGS). A full methodology of data collection and processing can be read in Dixit et al. (2022). There are five main commodities that represent major energy sources produced and consumed in the United States: (1) Oil and gas extraction, (2) Coal mining, (3) Electric power generation, transmission, and distribution, (4) Natural gas distribution, and (5) Petroleum refineries. The amount (MBtu) of petroleum, natural gas, coal, and electricity used by the United States industry sectors was collected and embedded into the Use table to compute energy embodied in commodities' production in MBtu/$. Since the energy use data was inserted in the IO model in energy units (MBtu), the output of the model was in MBtu/$ of a commodity. By multiplying this EE intensity with the cost of a material or service from the schedule of values (SOV), the EE was calculated for the case study building. Likewise, water is supplied by the aggregated Water, Sewage and Other Systems industry sector, which represents not just the water commodities but also other commodities relating to waste water and sewage. Consequently, this aggregated commodity was broken down into a water use commodity and the other commodity that represents all remaining commodities lumped together. For disaggregation, the share of water utilities in the total annual revenue of the aggregated commodity was sourced and applied. Finally, the water use data was integrated into the Use table and EW intensities of different commodities were computed as million gallons/$. Like EE, the costs of materials and services from the SOV were multiplied with these EW intensities, the total EW of the case study building was quantified.

In the third step, the EC and EW of different construction materials were computed. For each of the four energy sources (petroleum, natural gas, coal, and electricity), the carbon emission factors were gathered from the Energy Information Administration (USDOE). Using the energy source-specific carbon dioxide emissions, the EC of commodities representing construction materials was quantified. To compute the final EC and EW of construction materials, the schedule of values (SOV) was sourced for a university building and multiplied the EC and EW intensities of construction materials with their respective cost in the SOV. The university building is a recently constructed academic building with spaces such as, classrooms, conference rooms, seminar halls, laboratories, and offices. The building is 178,380 square foot facility with 4-5 floors. The system boundary of EC and EW calculation was cradle-to-site that covered raw material extraction, transportation, manufacturing, and final delivery of a material to a site or a warehouse. The focus was on analyzing the EC and EW of 14 main material groups that included concrete, concrete masonry unit (CMU), cut stone, structural steel, wood, damp-proofing/water-proofing membranes, flashing, drywall (gypsum), aluminum, glass, paint, flooring tiles (ceramic), carpet, and insulation. The total cost of these materials represents over 33% of the total construction cost of the university building.

Results

Table 1 lists the share of each of the 14 construction materials in the total construction cost of the university building. Note that these costs are of material used for construction and exclude materials for services and systems. The total construction cost of the building is $63,562,421. As seen in the table, the initial embodied energy (EE) intensities of construction material ranges from 11.36 kBtu/$ for CMU to 43.35 kBtu/$ for aluminum. This is quite different from the EW intensities, which are computed in the range of 2.43 gallons/$ for damp-proofing/water-proofing material to 14.0 gallons/$ for carpet. This means that EE and EW intensities may not share a correlation. In other words, a material selected for lower EE may not have a lower EW. This is particularly important for structural materials such as concrete and steel, which show that in terms of EE, concrete may be preferred, whereas in terms of EW, steel may be more preferable. However, note that these intensities are in per unit of $ and a unit dollar can buy varying quantities of these materials. Likewise, frequently used common floor finishes such as carpet and ceramic tiles may not differ much in their EE intensities but the EW intensity of carpet in nearly 3.6 times that of ceramic tiles. Materials such as wood has the second largest EW intensity among the studied 14 materials. Looking at the total EE, EC, and EW of these materials, therefore, may be more important.

Table 2 lists comparatively the total EE, EC, and EW per unit area of these materials used in the case study building. Based on the quantities of different materials used in the building, the EE, EC, and EW values vary significantly across the building. The total EE, EC, and EW values of the case study building are 802,940 MBtu, 94,305 ton CO_2, and 708,745 liter of water, respectively. The top three materials in term of the largest share in total EE and EC are structural steel, aluminum, and concrete, which are some of the most commonly and frequently used bulk construction materials in commercial buildings. The top three materials in terms of their share in the total EW include structural steel, concrete, and insulation. Surprisingly, aluminum, a highly energy and carbon-intensive material, ranks 8th in terms of its share in the total EW of the building. This further highlights the fact that even though the EW intensities of materials such as carpet, wood, and paint are the top three, materials that make up the most EW are steel, concrete, and insulation. Again, this is due to their bulk use in most commercial buildings.

Table 1

Construction cost share and EE and EW intensities of commodities representing materials

Construction material	Share in total cost (%)	Cost/m^2	EE intensity (kBtu/$)	EW intensity (gallons/$)
Concrete	5.27%	$18.77	18.67	5.28
CMU	3.24%	$11.56	11.36	3.05
Cut Stone	0.18%	$0.64	13.24	4.48
Structural Steel	10.50%	$37.42	25.94	3.59
Wood	0.74%	$2.62	19.00	10.06
Damp-/waterproofing	1.05%	$3.76	24.02	2.43
Flashing	0.22%	$0.80	14.23	2.75
Drywall/Gypsum Board	2.26%	$8.05	43.02	7.58
Aluminum	2.44%	$8.71	43.35	3.70
Glass	1.73%	$6.16	21.70	4.41
Paint	1.33%	$4.74	18.07	9.89
Flooring (Ceramic Tile)	0.60%	$2.14	15.77	3.94
Carpet	1.01%	$3.62	18.19	14.00
Insulation	3.07%	$10.93	23.83	6.10

Figure 2 demonstrates how each material differs in terms of EC for the same unit of EE. This further makes a strong case for considering energy- and non-energy-related carbon emissions when selecting construction materials. The results of EREW calculation show that each material also differs in its share of EREW in the total EW. The EREW's share in the total EW of the fourteen construction materials varies from 2.5% to 27%. This emphasize making design decisions of material and layout selection on the basis of EE, EC, and EW to ensure long-term holistic sustainability.

Table 2

Total EE, EC, and EW values of construction materials installed in the university building

	Concrete	CMU	Cut Stone	Structural Steel	Wood	Damp-proofing	Flashing	Drywall	Aluminum	Glass	Paint	Ceramic Tile	Carpet	Insulation
Embodied energy (MBtu/m^2)	0.35	0.13	0.01	0.97	0.05	0.09	0.01	0.35	0.38	0.13	0.09	0.03	0.07	0.26
Embodied carbon (kg/m^2)	38.71	15.30	0.98	115.03	5.02	7.06	1.51	33.74	60.17	14.63	8.09	3.34	7.25	31.53
Embodied water (liter/m^2)	0.38	0.13	0.01	0.51	0.10	0.03	0.01	0.23	0.12	0.10	0.18	0.03	0.19	0.25

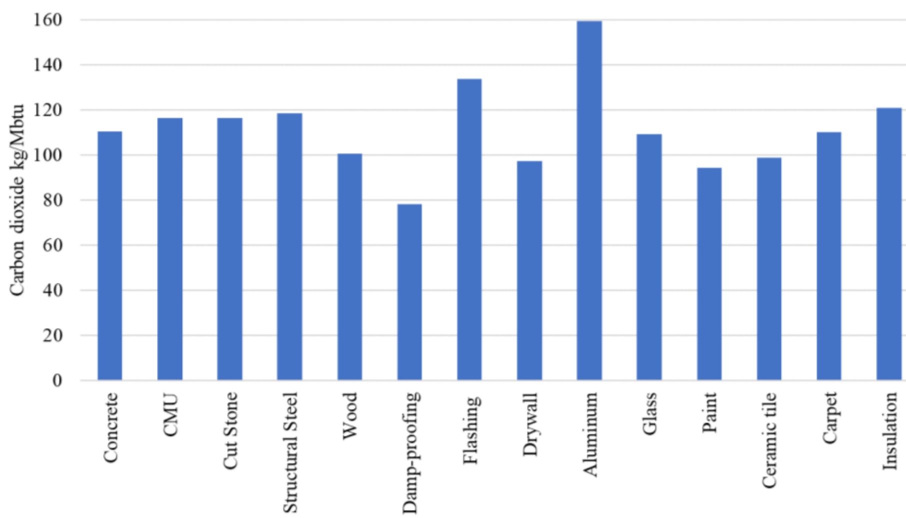

Figure 2. Total EE, EC, and EW values of construction materials installed in the university building

Discussion

The findings of this paper highlight three important aspects of the environmental sustainability of buildings. First, saving EE through material selection may help reduce EC but it may not decrease EW. Figure 3 shows two scatter plots. In the first scatter plot (left-hand side), the total EW of materials at the building level seems to share a strong positive correlation with the materials' EC. Due to this seemingly strong positive correlation, a regression analysis was run to test the correlation. An extremely small *Significance of F* (0.00042) indicated the unlikeliness that the correlation was random. Further, a smaller *p-value* (0.00042) indicated that the EC and EW demonstrate a high positive correlation with $r^2 = 0.66$. According to Chan (2003) and Taylor (1990), a coefficient of determination in the range of 0.64-0.81 indicates a strong correlation. This may lead us to believe that saving EC may result in saving EW, which may be true. However, not all EW may be reduced by decreasing the EC of materials since only 2.5%-27% of the total EW can be attributed on EREW. This means that additional design strategies may be needed to lower the total EW of a building and its materials. Note that the strong positive EC-EW correlation in the left-hand side scatter plot in Figure 3 may be driven by the one point at the far end. More detailed correlation analysis may be needed to further study this correlation. The second scatter plot (right-hand side scatter plot in Figure 3) shows that the strong positive correlation becomes extremely weak at the material intensity level. Since the correlation seemed weaker, a regression analysis was not run for this correlation. This weaker correlation may get stronger at the building level due to material quantities; a lower EW material may cause more EW use at the building level simply because its quantity used in the building is higher. Second, at the whole building level, the indirect components of EE and EW represent a significant portion of the total EE and EW. The fourteen materials that represented roughly 1/3rd of the total construction cost of the university building contribute to nearly 65% of the total EE and 60% of the total EW of the building. This point to the huge role construction materials may play in reducing the energy and resource burdens of buildings. This information is critical to design decision making by designers, especially during material and layout selection. Third, a building design optimized for EE may not have the least EW. In other words, optimizing a building's environmental performance from EE, EC, and EW standpoint is a multi-objective problem with conflicting objectives achieving which may need computational algorithms such as multi-objective genetic algorithm (MOGA).

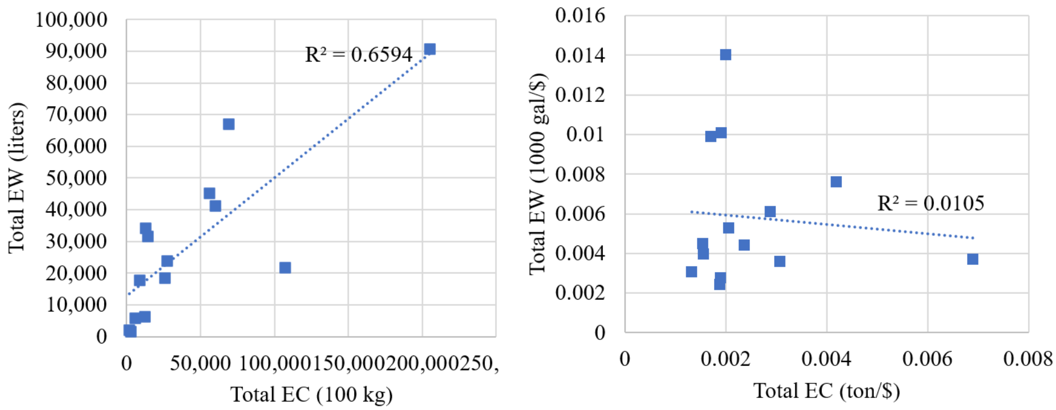

Figure 3. Correlation of EC and EW at the whole building and per $ intensity levels

Conclusions

The main goal of this paper was to understand the EE, EC, and EW impacts of construction materials and compare their impacts at the building level. Two IOH macroeconomic models were designed using the latest IO data for the United States economy to compute EE and EW intensities of construction material commodities. Using the SOV of a university building project, the EE, EC, and EW of fourteen major construction materials conventionally used in commercial building construction were computed. The results indicate that the total EE, EC, and EW values of the case study building are 4.5 MBtu/ ft^2, 528.7 $kgCO_2/ft^2$, and 1,049.6 gallon/ft^2. Moreover, the total EE and EW of the fourteen construction materials vary in the range of 0.1-11.0 MBtu/ft^2 and 2.2-134.3 gallon/ft^2. This means that two materials with the same function in a building must be analyzed by the architects and engineers not just for energy impacts but also for carbon emission and water use impacts. For instance, concrete and steel both can be used as structural material but the two have different energy and water footprint that must be carefully analyzed before selecting one material over the other. The findings further suggest that EE savings may convert to proportional savings in EC. However, reducing EE may not decrease EW, and decreasing EW of a building may require specific design strategies involving the selection of low EW materials. This shows that optimizing all three dimensions of energy use, carbon emissions, and water use at the building level may be complicated and may require generating most possible alternatives to create a population of design alternatives and select the most optimal solution. This underscores the significance of designing computational algorithms such as a multi-objective optimization (MOO) that help find design solutions with not just low EE and EC but also the least amount of EW. The results have clear educational implications. Undergraduate and graduate students are future construction managers, entrepreneurs, policymakers, constructors, and homebuilders. They must learn how their professional decisions may influence the energy, carbon, and water flows in the construction sector influencing its environmental footprint.

References

Azari, R., & Abbasabadi, N. (2018). Embodied energy of buildings: A review of data, methods, challenges, and research trends. Energy and Buildings, 168, 225-235.

Bardhan, S., Choudhuri, I.R., 2016. Studies on virtual water content of urban buildings in India. *Indian Journal of Science and Technology* 9 (2016): 6.

Bardhan, S., 2011. Assessment of water resource consumption in building construction in India. *WIT Trans. Ecol. Environ* 144 (2011): 93-101.
Chan, Y. H. (2003). Biostatistics 104: correlational analysis. Singapore Medical Journal, 44(12), 614-619.
Chang, Y., Huang, Z., Ries, R.J., Masanet, E., 2016. The embodied air pollutant emissions and water footprints of buildings in China: a quantification using disaggregated input–output life cycle inventory model. *Journal of Cleaner Production* 113 (2016): 274-284.
Chen, S., Tan, Y., & Liu, Z. (2019). Direct and embodied energy-water-carbon nexus at an inter-regional scale. Applied Energy, 251, 113401.
Choudhuri, I.R., 2015. Assessment of Embodied Water of Construction: Case Study of a Four Star Rated Hotel in New Delhi, India. *International Journal* 195 (2015).
Choudhuri, I. (2015b). Pre-Operational Water of Construction: case study of a commercial complex in Pune, India. International Journal of Science, Engineering and Technology, 3(5), 1136-1139.
Choudhury, I.R., Roy, S., 2015. Significance of Pre-operational Embodied Water of Buildings in Innovative & Sustainable Design Practices. The Institution of Engineers (Pune) Local Centre, Technical Journal Vol. No. 39, 74-78.
Collinge, W. O., Landis, A. E., Jones, A. K., Schaefer, L. A., & Bilec, M. M. (2013). Dynamic life cycle assessment: framework and application to an institutional building. The International Journal of Life Cycle Assessment, 18(3), 538-552.
Crawford, R., Treloar, G., 2005. An assessment of the energy and water embodied in commercial building construction. In *Australian Life Cycle Assessment Conference (4th: 2005: Novotel, Sydney, NSW)*, pp. 1-10. Australian Life Cycle Assessment Society, 2005.
Dascalaki, E. G., Argiropoulou, P., Balaras, C. A., Droutsa, K. G., & Kontoyiannidis, S. (2021). Analysis of the embodied energy of construction materials in the life cycle assessment of Hellenic residential buildings. Energy and Buildings, 232, 110651.
Dixit, M. K., Kumar, P. P., & Haghighi, O. (2022). Embodied water analysis of higher education buildings using an input-output-based hybrid method. Journal of Cleaner Production, 365, 132866.
Dixit, M.K., Singh, S., 2018. Embodied energy analysis of higher education buildings using an input-output-based hybrid method. Energy Build. 161, 41–54. https://doi.org/10.1016/j.enbuild.2017.12.022
Grubert, E., Sanders, K.T., 2018. Water Use in the United States Energy System: A National Assessment and Unit Process Inventory of Water Consumption and Withdrawals. Environ. Sci. Technol. 52, 6695–6703. https://doi.org/10.1021/acs.est.8b00139
Hendriks, C. A., Worrell, E., De Jager, D., Blok, K., & Riemer, P. (1998, August). Emission reduction of greenhouse gases from the cement industry. In Proceedings of the fourth international conference on greenhouse gas control technologies (pp. 939-944). IEA GHG R&D Programme Interlaken, Austria.
Hong, J., Zhong, X., Guo, S., Liu, G., Shen, G.Q., Yu, T., 2019. Water-energy nexus and its efficiency in China's construction industry: Evidence from province-level data. *Sustainable Cities and Society* 48 (2019): 101557.
Hu, M. (2020). A Building life-cycle embodied performance index—The relationship between embodied energy, embodied carbon and environmental impact. Energies, 13(8), 1905.
Junnila, S., Horvath, A., & Guggemos, A. A. (2006). Life-cycle assessment of office buildings in Europe and the United States. Journal of Infrastructure systems, 12(1), 10-17.
Krogmann, U., Minderman, N., Senick, J., & Andrews, C. J. (2008). Life-cycle assessment of New Jersey Meadowlands Commission Center for environmental and scientific education building. Rutgers Center for Green Building, New Brunswick, New Jersey, USA.
Li, X., Feng, K., Siu, Y.L., Hubacek, K., 2012. Energy-water nexus of wind power in China: the balancing act between CO2 emissions and water consumption. *Energy policy* 45, 440-448.

McCormack, M., Treloar, G.J., Palmowski, L., Crawford, R., 2007. Modelling direct and indirect water requirements of construction. *Building research and information* 35, no. 2, 156-162.
Mellor, A.E., 2017. Assessing water footprint and associated water scarcity indicators at different spatial scales: a case study of concrete manufacture in New Zealand, Master's thesis, Massey University, Manawatu Campus, New Zealand. PhD diss., Massey University, 2017.
Meng, J., Chen, G.Q., Shao, L., Li, J.S., Tang, H.S., Hayat, T., Alsaedi, A., Alsaadi, F. (2014). Virtual water accounting for building: case study for E-town, Beijing. Journal of cleaner production 68, 7-15.
Mousavi, S., Kara, S., Kornfeld, B., 2015. Assessing the impact of embodied water in manufacturing systems. *Procedia CIRP* 29, 80-85.
Nizam, R. S., Zhang, C., & Tian, L. (2018). A BIM based tool for assessing embodied energy for buildings. Energy and Buildings, 170, 1-14.
Pullen, S., Chiveralls, K., Zillante, G., Palmer, J., Wilson, L., Zuo, J., 2012. Minimising the impact of resource consumption in the design and construction of buildings. Griffith University.
Rasmussen, F. N., Malmqvist, T., Moncaster, A., Wiberg, A. H., & Birgisdóttir, H. (2018). Analysing methodological choices in calculations of embodied energy and GHG emissions from buildings. Energy and buildings, 158, 1487-1498.
Rossello-Batle, B., Ribas, C., Moia-Pol, A., & Martínez-Moll, V. (2015). Saving potential for embodied energy and CO2 emissions from building elements: A case study. Journal of Building Physics, 39(3), 261-284.
Scheuer, C., Keoleian, G. A., & Reppe, P. (2003). Life cycle energy and environmental performance of a new university building: modeling challenges and design implications. Energy and buildings, 35(10), 1049-1064.
Sharma, A., Shree, V., & Nautiyal, H. (2012). Life cycle environmental assessment of an educational building in Northern India: A case study. Sustainable Cities and Society, 4, 22-28.
Strezov, V., Evans, A., Evans, T., 2013. Defining sustainability indicators of iron and steel production. Journal of cleaner production, 51, 66-70.
Taffese, W. Z., & Abegaz, K. A. (2019). Embodied energy and CO2 emissions of widely used building materials: the Ethiopian context. Buildings, 9(6), 136.
Taylor, R. (1990). Interpretation of the correlation coefficient: a basic review. Journal of Diagnostic Medical Sonography, 6(1), 35-39.
Treloar, G., Crawford, R., 2004. Assessing direct and indirect water requirements of construction. In ANZAScA 2004: Contexts of architecture: proceedings of the 38th Annual Conference of the Architectural Science Association ANZAScA and the International Building Performance Simulation Association, pp. 186-191. University of Tasmania, 2004.
Venkatraj, V., Dixit, M.K., 2021. Life cycle embodied energy analysis of higher education buildings: A comparison between different LCI methodologies. Renewable and Sustainable Energy Reviews, 144, 110957.
Wu, X.D., Chen, G.Q., 2017. Energy and water nexus in power generation: The surprisingly high amount of industrial water use induced by solar power infrastructure in China. *Applied energy* 195, 125-136.

Identifying Sustainability Claims by Roof Type Utilizing Standards and Certifications from Manufacturers

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One of the essential elements of the built environment is the roofing system since it provides protection form environmental and natural elements. Therefore, roofing can play a critical role in sustainability via energy efficiency for any facility. Roofing manufacturers play a crucial role in the roofing industry, especially since the majority of the roofing materials are manufactured in the United States; however, exported to the world. The performance of a roof varies according to the type of roof, and each type has its own advantages and disadvantages as it relates to sustainability. Various roofing manufacturers make claims on various sustainability factors such as (a) UV Resistance, (b) Ozone Resistance, (c) Durability, (d) Energy Efficiency, (e) Emissivity, and (f) Environment Friendly. This study documents and evaluates the basis of sustainability claims of various types of roofing materials/systems. Sustainability claims were mapped and categorized with industry standards and certifications. Text analysis was performed by organizing and evaluating unstructured text from websites, brochures, technical data sheets, and specifications from seventeen roofing manufacturers. The current study allowed a visualized map among roofing manufacturer products, standards, certifications, and testing procedures with multiple sustainability claims.

Keywords: Roofing sustainability, built environment, sustainable development, roof types

Introduction

The U.S. Buildings are ubiquitous and form an integral part of society and life (Buyle et al., 2013). More than 20% of the world's CO2 emissions are currently attributed to the construction industry. Moreover, over 30% of the world's CO2 emissions come from the operation and maintenance of buildings (Faber, 2020). The construction industry practices do not positively impact the environment in terms of using the material, construction, and building operations (Ding, 2008). Building performance and minimizing its effect on the natural environment have become an important topic of interest as part of sustainable growth (Sev, 2009). On the other hand, demand for an ecologically sustainable built environment is increasing worldwide (Zhang et al., 2014).

The term sustainable development covers a broad range of definitions. However, generally it is defined as attitudes and judgment to help ensure long-term ecological, social, and economic growth in society (Ding, 2008). It is also defined as the environment's ability to sustain the present needs without compromising the ability of future generations to meet their goals and ambitions. Given the built environment's impact on sustainability, it is critical to design sustainability solutions from the early project life phases (Mésároš et al., 2021).

One of the essential elements of the built environment is the roofing system since it provides protection from environmental and natural elements. Therefore, roofing can play a critical role in sustainability via energy efficiency for any facility. However, roofing is generally overlooked in the design phase since it does not form the key aesthetical element of the building façade for commercial sectors. The roofing industry comprises manufacturers, distributors, and contractors. Roofing manufacturers play a critical role in the roofing industry, especially since most of the roofing materials are manufactured in the United States; however, they are exported worldwide. The common types of roofing systems used in the roofing industry today include single-ply systems such as Thermoplastic Polyolefin (TPO), Polyvinyl Chloride (PVC), Ethylene Propylene Diene Terpolymer (EPDM). Multi-ply systems, also known as bituminous roofing systems (BR), such as BUR (Built-up Roof) and Modified Bitumen (MB), are also beingused in the roofing industry.

The performance of a roof varies according to the type of roof, and each type has its advantages and disadvantages as it relates to sustainability (Abuseif & Gou, 2018). Many claims have been made by various roofing manufacturers on their specific roofing systems as it relates to energy efficiency and sustainable performance. The previous studies conducted in the roofing industry are focused on the energy performance of built environment systems primarily during the operational phase of the facility (Taylor, 2019). Studies have also investigated energy efficiency, life cycle assessment, r-value, u-value, albedo, and reflectance and their effects on Urban Heat Island (O'Malley et al., 2014; Shickman & Rogers, 2019; Shimoda et al., 2004; Susca & Pomponi, 2020).

The sustainability claims commonly used by roofing manufacturers are (a) UV Resistance, (b) Ozone Resistance, (c) Durability, (d) Energy Efficiency, (e) Emissivity, and (f) Environment Friendly. UV resistance of a roof refers to the material's capacity to avoid UV radiation deterioration induced by UV absorption (Radius, 2021). Ozone Resistance in roofing refers to the ability of a membrane to withstand the effects of exposure to ozone (Rubber, 2022). Durability refers to weathering, fire, crack, and heat resistance, and waterproofing. Energy efficiency refers to the degree of efficiency that a roof plays in the amount of solar radiation absorbed by roofs in hot weather and the amount of heat lost through roofs in cold weather (Abuseif & Gou, 2018). Emissivity is described as the ability of roofing products to release absorbed heat (Star, 2022). A common term used as a factor by roofing manufacturers is "environment friendly." Based on the literature, it is closely defined as eco-friendly and environmentally safe (Siplast, 2022).

However, there are no studies documenting the basis of the product claims for various manufacturers and their products for sustainability. The basis of the claims needs to be verified against standards and industry certifications as roofs play a crucial role in various early design decisions, life cycle costing, and analysis for facilities as part of sustainable approaches (Khanum, et al., 2021; Rosasco & Perini, 2019; Cubi et. al, 2015).

Manufacturers are using a variety of organizations and third-party certifications for sustainability claims, such as:

- Cool Roof Rating Council (CRRC) program certifying roofing products on solar reflectance and thermal emittance (CRRC, 2022)
- Energy Star labeling and certifying roofing products qualified for saving the measurable amount of energy(Star, 2022)
- California Title 24 is a standard used to guarantee that both new and existing buildings are energyefficient and maintain both indoor and outdoor environmental quality (Title24Express, 2021)
- ISO is the international standard for a quality management system.
- Leadership in Energy and Environmental Design (LEED) is a building rating system used to certify buildings with environmental and energy conservation goals.
- FM Standard evaluates single-ply, polymer-modified bitumen sheet, BUR (built-up roofing), and liquid-applied roof assemblies for their performance regarding fire from above and below the structural deck (WesternColloid, 2022).
- American Society for Testing and Material (ASTM) rates or confirm product quality (durability, emissivity, solar reflectance, and UV resistance). The various ASTM standards used by roofing manufacturers are shown in *Table 1*.

Table 1

ASTM Standard Types & Sustainability Factors

Standards	UV	OR	D	HEFP	HSR	E	EF
ASTM D4601	×	×	✓	×	×	×	×
ASTM D2178	×	×	✓	×	×	×	×
ASTM D 622	×	×	✓	×	×	×	×
ASTM D 6164	×	×	✓	×	×	×	×
ASTM D570	×	×	×	×	×	×	×
ASTM G154	✓	×	✓	×	×	×	×
ASTM C1549	×	×	×	×	✓	×	×

ASTM C1371	×	×	×	×	×	✓	×
ASTM D4434	×	×	✓	×	×	×	×
ASTM D4637	×	×	✓	×	×	×	×
ASTM D6878	×	×	✓	×	×	×	×

UV - UV Resistance; OR – Ozone Resistance; D – Durability; HEFP – High Energy Efficiency Performance; HSR – High Solar Reflectance; E – Emissivity; EF – Environmentally Friendly

This study documents and evaluates the basis of sustainability claims of various types of roofing materials/systems. It investigates the logical path such as standards and certifications used for any of the claims. The objectives of this study are to 1) identify the types of sustainability claims used by various roofing manufacturers, 2) map and categorize the claims with industry standards and certifications, and 3) collect and categorize the claims against deficiencies.

Methods

The goal of the study was to document and evaluate sustainability claims regarding roofing products from seventeen. (17) major manufacturers identified in the United States. The methodology for this study is shown in *Figure 1* below.

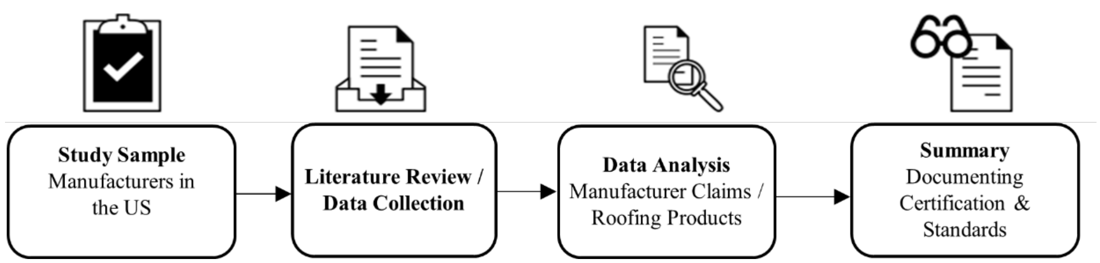

Figure 1. Study overview

A steering committee comprised of four major manufacturers in the roofing industry was created to guide the study framework, sustainability factors, and validation. The seventeen (17) manufacturers represented most of the roofing manufacturers in the roofing industry and holds 70 to 80 percent of the US roofing market. Text analysis was performed by organizing and evaluating unstructured text. Text analysis consisted of identifying key sustainability terms across each manufacturer's website, brochures, technical data sheets, and specifications. The claims from various sources regarding sustainability were identified fordifferent roofing products. A detailed literature review for various industry standards and certifications was conducted prior to mapping and categorizing various claims for each identified standard. For example, various claims relevant to sustainability for PVC roofing product from each manufacturer was further categorized into the following sustainability factors (a) UV Resistance, (b) Ozone Resistance, (c) Durability, (d) Energy Efficiency, (e) Emissivity, and (f) Environment Friendly.

Analysis and Discussion

Study sample

Table 2 shows the number of manufacturers that produce the different types of roofing systems. Nine (9) out of seventeen (53%) manufacturers made TPO, seven (7) out of seventeen (41%) manufacturers produced PVC, seven (7) manufacturers out of seventeen (41%) produced EPDM, and only four (4) manufacturers out of seventeen(24%) produced BR.

Table 2

Study Sample – Roof Types by Manufacturers

Manufacturers*	TPO	PVC	EPDM	BR
A*	✓	×	✓	×
B*	✓	✓	✓	×
C*	✓	✓	✓	×
D*	✓	×	✓	×
E*	×	×	×	✓
F*	×	×	×	✓
G*	×	✓	×	✓
H*	×	×	×	×
I*	×	×	×	×
J*	×	✓	×	×
K*	×	×	×	×
L*	×	✓	×	×
M*	✓	×	×	×
N*	✓	✓	×	✓
O*	✓	×	✓	×
P*	✓	✓	✓	×
Q*	✓	×	✓	×

Manufacturers Claims and Roofing Products

Figure 2 shows the various claims relevant to sustainability for all roofing products from each manufacturer categorized into the sustainability factors identified for this study. 70% of the manufacturers claimed that their roofing products exhibit UV Resistance, 35% of the manufacturers claimed that their roofing products exhibit Ozone Resistance, 100% of the manufacturers claimed that their roofing products are Durable, 52% of the manufacturers claimed that their roofing products have high Energy Efficiency Performance, 82% of the manufacturers claimed that their roofing products have high Solar Reflectance and 26% manufacturers claimed that their roofing products have good Emissivity, and 47% manufacturers claimed that their roofing products are Environment-friendly. Based on the data collection, TPO, PVC and EPDM roofing products claimed all the properties related to sustainable factors, namely, UV Resistance, Ozone Resistance, Durability, High Energy Efficiency Performance, High Solar Reflectance, Emissivity, and Environmental-friendly. Bituminous only claimed properties related to UV Resistance, Durability, High Energy Efficiency Performance, and High Solar Reflectance.

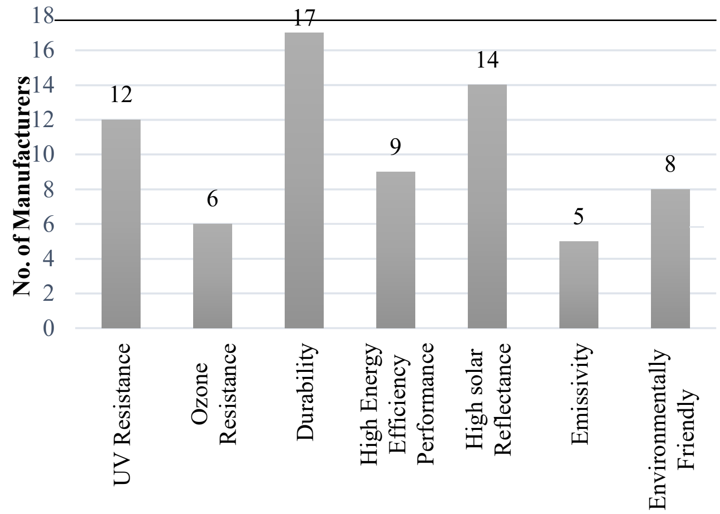

Figure 2. Sustainability Claims by Roofing Manufacturers

Figure 3 shows the various claims relevant to sustainability for TPO, PVC, BR, and EPDM roofing systems from each manufacturer categorized into the sustainability factors identified for this study. 78% of the TPO Roofing manufacturers claimed their products exhibit durability and high energy efficiency performance. 67% of the TPO roofing manufacturers claimed their products exhibit UV resistance and high solar reflectance. 55% of the TPO roofing manufacturers claimed their products show ozone resistance and are environmental-friendly. 33% of TPO roofing manufacturers claimed their products exhibit emissivity as one of the key properties. Similar claims for PVC, BR, and EPDM products are also shown. Interestingly, only one out of seven made any claims about ozone resistance andemissivity for PVC products, whereas no manufacturer for BR claimed about ozone resistance, environmental friendly and emissivity. For EPDM, the majority of the manufacturers showed benefits around durability and ozone factors.

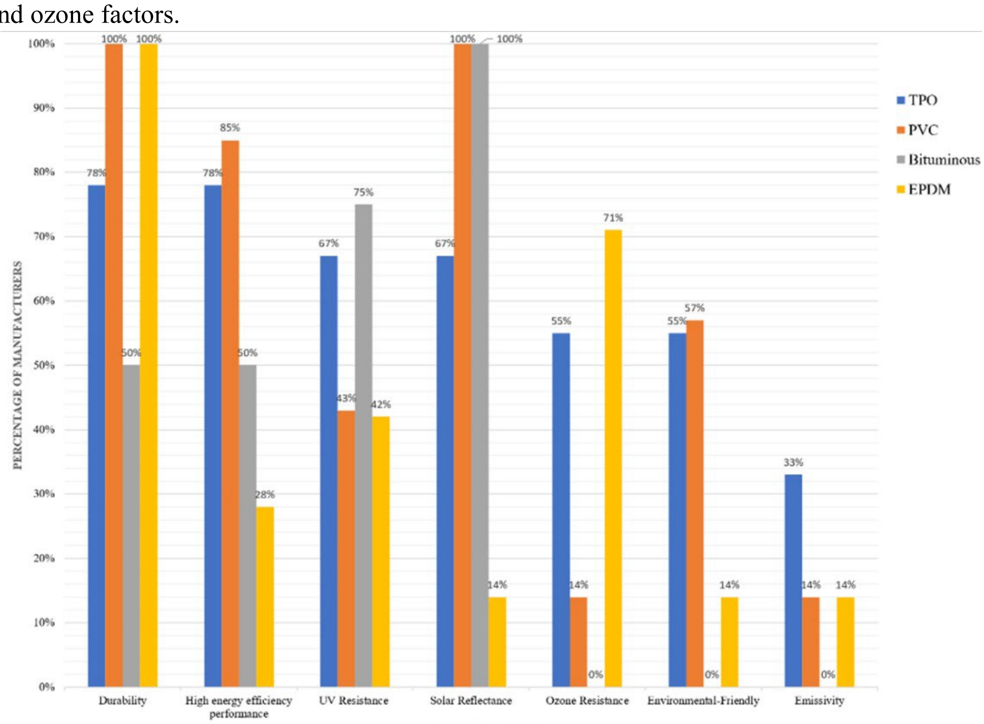

Figure 3. Roofing Manufacturer's Sustainability Claims by Roof Type

Further, sustainability claims of various roofing products were mapped to industry standards and certifications, asshown in Table 3. Manufacturers adopted certifications such as CRRC, Energy Star, California Title 24, LEED, and ASTM to support their claims for various roofing products. There is no documentation that shows any industry standards, certifications, or testing used as a basis for Ozone Resistance for various roofing products. ASTM G154 and LEED credits are the only standards and prescriptive requirements that require environmentally friendly and UV resistance approaches for various roofing products. The claim by manufacturers for high energy efficiency performance is supported by standards namely, Energy Star and California Title 24. The claim of highsolar reflectance is supported by means namely, CRRC, Energy Star, California Title 24, FM Standard 4470, and ASTM C1549. It is evident that only three (3) standards have been used by manufacturers to support the claimof "high energy efficiency performance," six (6) standards to validate the claim of "high solar reflectance," and three (3) standards for "emissivity." TPO used five different standards, PVC used seven standards, and BR used six standards. However, EPDM manufacturers only used ASTM C1549, ASTM C1371, and ASTM D4637, which primarily emphasized solar reflectance, emissivity, and tensile strength.

Table 3

Sustainability Factors and Standards/Certifications by Roofing Type

Standards	TPO	PVC	EPDM	BR	Sustainability Factors
CRRC	✓	✓	×	×	Solar Reflectance, Emissivity
Energy Star	✓	✓	×	×	Energy Efficiency, Solar Reflectance And Emissivity
California Title 24	✓	✓	×	×	Energy Efficiency, Solar Reflectance And Emissivity
LEED	✓	✓	×	×	Energy Efficiency, Emissivity, Environmental Friendly
ISO 9001:2015	×	×	×	✓	Effective Application of The Roofing System
ASTM D4601	×	×	×	✓	Crack Resistant
ASTM D2178	×	×	×	✓	Waterproofing
FM Std. 4470	×	×	×	✓	Water-leakage, Corrosion of Metal Parts
ASTM D 622	×	×	×	✓	Waterproofing
ASTM D 6164	×	×	×	✓	Waterproofing
ASTM D570	×	✓	×	×	Water Absorption of Plastic
ASTM G154	×	✓	×	×	UV Resistance Test
ASTM C1549	×	×	✓	×	Solar Reflectance
ASTM C1371	×	×	✓	×	Emissivity
ASTM D4434	×	✓	×	×	Fire Resistance, Wind Uplift Resistance
ASTM D4637	×	×	✓	×	Tensile Strength
ASTM D6878	✓	×	×	×	Weather Exposure (Only For TPO)

Conclusion

The study documented and evaluated the basis of sustainability claims of various types of roofing materials/systems. It investigated the logical path such as standards and certifications used for any of the claims by roofing manufacturers for various roofing products such as TPO, PVC, EPDM and BR. Specifically, this study identified the types of sustainability claims used by various roofing manufacturers and mapped/categorized the claims with industry standards and certifications.

The current study allowed a visualized map among roofing manufacturer products, standards, certifications and testing procedures with multiple sustainability claims. The sustainability claims were documented primarily based on external accreditation and standards and not supported by peer-reviewed published studies. The degree ofimpact on various sustainability factors, such as reflectance, emissivity, etc., was also not documented onthe manufacturer's website, brochures, technical data sheets, and specifications. For example, high solar reflectance was claimed by one (1) EPDM manufacturer, six (6) TPO manufacturers, seven (7) PVC manufacturers, and four.

(4) BR manufacturers out of a total of seventeen (17) manufacturers. However, it lacked any documentation on numerical validation or support from peer-revied publications. A few manufacturer claims werenot supported by any certification, standards, or published studies.

For future study, the different components of the roofing need to be verified as a system against sustainability claims. Manufacturers play a crucial role in roofing sustainability thus the role of roofing manufacturers in sustainability should be studied in addition of their perspective towards sustainability. And this study paves a way to study sustainability claims for other sectors in the construction industry. Also, the degree of impact needs to be documented for user applicability against peer-reviewed research. A systematic literature review to document various sustainability claims to provide a degree of impact by various roof types is needed. As for limitations, the study only focused on the sustainability claims from the roofing industry. Roofing warranties lie between five years to lifetime, and the roofing replacement interval is not considered for this research. This study paves the way to study sustainability claims for other sectors in the construction industry.

References

Abuseif, M., & Gou, Z. (2018). A review of roofing methods: Construction features, heat reduction, payback period and climatic responsiveness. In Energies (Vol. 11, Issue 11). MDPI AG. https://doi.org/10.3390/en11113196

Buyle, M., Braet, J., & Audenaert, A. (2013). Life cycle assessment in the construction sector: A review. In Renewable and Sustainable Energy Reviews (Vol. 26, pp. 379–388). https://doi.org/10.1016/j.rser.2013.05.001

CRRC. (2022). Retrieved from https://coolroofs.org/programs/roof-rating-program.

Cubi, E., Zibin, N. F., Thompson, S. J., & Bergerson, J. (2015). Sustainability of rooftop technologies in cold climates: Comparative life cycle assessment of white roofs, green roofs, and photovoltaic panels. Journal of Industrial Ecology, 20(2), 249–262. https://doi.org/10.1111/jiec.12269

Faber, M. H. (2020). GLOBE–Global Consensus on Sustainability in the Built Environment—Report. Structural Engineering International, 30(4), 600–601. https://doi.org/10.1080/10168664.2020.1823753

Gibberd, J. (2015). Measuring capability for sustainability: The Built Environment Sustainability Tool (BEST). Building Research and Information, 43(1), 49–61. https://doi.org/10.1080/09613218.2014.930257

Khanum, Z. S., Kumara, A. V., & Ram, H. (2021). Studies on Sustainability Aspects of Building with Different Roofing Systems and Block Work. Turkish Journal of Computer and Mathematics Education, 12(10), 138-150.

Mésároš, P., Spišáková, M., Mandičák, T., Čabala, J., & Oravec, M. M. (2021). Adaptive design of formworks for building renovation considering the sustainability of construction in BIM environment-case study. Sustainability (Switzerland), 13(2), 1–20. https://doi.org/10.3390/su13020799

O'Malley, C., Piroozfarb, P. A. E., Farr, E. R. P., & Gates, J. (2014). An investigation into minimizing urban heat island (UHI) effects: A UK perspective. Energy Procedia, 62, 72–80. https://doi.org/10.1016/J.EGYPRO.2014.12.368

Radius, F. (2021). Fast Radius. Retrieved from https://www.fastradius.com/resources/top-uv-resistant-plastics/

"Roofers: Occupational Outlook Handbook" (2022) *U.S. Bureau of Labor Statistics*, U.S Bureau of Labor Statistics

Rosasco, P., & Perini, K. (2019). Selection of (green) roof systems: A sustainability-based multi-criteria analysis. Buildings, 9(5), 134. https://doi.org/10.3390/buildings9050134

Rubber, M. (2022). MacLellan Rubber. Retrieved from https://maclellanrubber.com/definitions/ozone-weather-resistance

Sev, A. (2009). How can the construction industry contribute to sustainable development? A conceptual framework. Sustainable Development, 17(3), 161–173. https://doi.org/10.1002/sd.373

Shickman, K., & Rogers, M. (2019). Capturing the true value of trees, cool roofs, and other urban heat island mitigation strategies for utilities – ProQuest

https://www.proquest.com/docview/2210796035?parentSessionId=kzsdXCY%2BctwF2397UwGdCKv3nvA0WR1M1k%2FhpVUS9q8%3D&pq-origsite=primo&accountid=6167

Shimoda, Y., Fujii, T., Morikawa, T., & Mizuno, M. (2004). Residential end-use energy simulation at City Scale. Building and Environment, 39(8), 959–967. https://doi.org/10.1016/j.buildenv.2004.01.020

Siplast. (2022). Retrieved from http://www.siplast.com/~/media/IcopalUS/PDFs/2%20Siplast%20SBS.pdf

Sokas, R. K., Dong, X. S., & Cain, C. T. (2019). Building a sustainable construction workforce. *International Journal of Environmental Research and Public Health*, *16*(21). https://doi.org/10.3390/ijerph16214202
Star, E. (2022). Retrieved from https://www.energystar.gov/products/roof_products/cool_roofs_emissivity

Star, E. (2022). Retrieved from https://www.energystar.gov/buildings/building_recognition/building_certification#:~:text=ENERGY%20STAR%20certified%20buildings%20save,performance%20standards%20set%20by%20EPA.

Susca, T., & Pomponi, F. (2020). Heat island effects in urban life cycle assessment: Novel insights to include the effects of the urban heat island and uhi-mitigation measures in LCA for effective policy making. Journal of Industrial Ecology, 24(2), 410–423. https://doi.org/10.1111/jiec.12980

Taylor, T. J. (2019). Reflective roofing use on commercial buildings in the United States: An energy type and cost analysis. Buildings, 9(10). https://doi.org/10.3390/buildings9100212

Title24Express. (2021). Retrieved from https://www.title24express.com/what-is-title-24/

WesternColloid. (2022). Retrieved from https://westerncolloid.com/what-does-it-mean-when-a-product-is-fm4470-approved-for-hail/

Zhang, X., Wu, Y., Shen, L., & Skitmore, M. (2014). A prototype system dynamic model for assessing the sustainability of construction projects. International Journal of Project Management, 32(1), 66–76. https://doi.org/10.1016/j.ijproman.

Is the Construction Industry More Concentrated After the COVID-19 Pandemic? An Empirical Study on the U.S. Revenue Data from 2004 to 2021

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As a most important industry in the U.S., the construction industry faces multiple challenges since the COVID-19 pandemic. Backed by government interventions that have helped streamline construction projects, however, the aftermath of the pandemic is still vague. One of the imperative issues to be examined is the construction market concentration since the pandemic, especially how it is compared to the Great Recession. This study statistically analyzes the revenue gaps among the U.S. construction companies and the changes of their revenue rankings. This study uses the data from Engineering News-Record Top List of Contractors. The results show that unlike the Great Recession, which obviously enlarged the revenue gaps, there is no evidence yet demonstrating that the COVID-19 pandemic caused noteworthy disruptions to the revenue gap among construction companies. The government interventions, such as the Paycheck Protection Program and the Infrastructure Investment and Job Act, are regarded as effective stabilizers, until the cutoff of data collection at the beginning of 2022. The medians of ranking changes across years generally remain stable, including the period of pandemic. The study also indicates the necessity to include more longitudinal data and sectional data to explore long-term impacts and sector-wise conditions.

Key Words: COVID-19, Construction Industry, Market Concentration, Empirical Study

Introduction

The toll of the COVID-19 pandemic affecting the global economy has been significant. The U.S. construction industry is no exception. It is shadowed by the general economic status of the nation, albeit being declared as an essential business during the stay-at-home orders. Many owners canceled their projects, causing delays in the completion of ongoing projects and increasing the construction cost (AIA Group 2020). Thanks to the continuous government interventions, such as the Paycheck Protection Program and the Covid-19 Relief Package, many construction projects that were halted due to the pandemic have been back on track (Karakaplan 2021). Nonetheless, many firms in the construction industry continue to experience the after-effects of the pandemic, such as a shortage of construction materials and rising inflation, which lead to increased competition and decreased profits. Despite the optimistic view towards the construction industry by the chief economist of Associated Builders and Contractors (Obando 2022), the United States has practically entered a recession after two consecutive quarters of economic contraction, according to the data by the Bureau of Economic Analysis as of the second quarter of 2022 (BEA 2022).

Looking back at the Great Recession, firms in the construction industry diverged greatly in their responses to the recovery from the unprecedented crisis starting from December 2007 (Biörck et al. 2020). The construction firms in the bottom quintile were hit much more severely by the disruption. A quarter of those bottom-quintile firms failed to make a profit, while more than a quarter of the top-quintile firms made positive returns (Biörck et al. 2020). In the age of corporation inequality, a small percentage of top-earning companies earn significantly more profits than their competitors (Bloom 2017). Moreover, these top-earning companies are more and more likely to maintain their dominant positions, while other corporations are less and less likely to grow and become profitable (Govindarajan et al., 2019). Many businesses outside the top tier are vulnerable to changes in circumstances over which they have no control, such as an economic crisis or a pandemic. As a result, they exhibit relatively low resilience in terms of adaptability and flexibility (Smallbone et al. 2012).

Researchers have introduced varied perspectives to explain the unbalanced impacts by the Great Recession to construction companies at different sizes. For instance, Tansey et al. (2014) found that contractors gained resilience by tending to adopt the most differentiation strategies, which help distinguish themselves from their competitors. The discussions originally focusing on the economic downturn during the Great Recession resume when there are accumulating evidences on the arrival of a new, post-pandemic economic downturn. For example, Bistrova et al. (2021) suggest that in order to survive the economic downturns caused by the COVID-19 pandemic, businesses should be more innovative, flexible, and productive than their competitors.

Before proceeding with the discussion, it is necessary to examine if the revenue gaps among construction companies are widened since the pandemic, like what happened during the Great Recession. Or if the pandemic brings opportunities to many companies by narrowing the gap between giants and others? It is also unclear if the pandemic consolidates the rankings or brings more changes to the rankings. The exploration on the revenue and the exploration on the change of revenue ranking echo the above-mentioned studies by Bloom (2017) and Govindarajan et al. (2019), respectively. Revenue reflects cross-sectional status, while the change of rankings indicates trends. Even though Phillips and Bousquin (2021) assert that the COVID-19 has ununiformly affected construction companies through soaring material prices and increased competition, it is neither endorsed by empirical data nor rigorous statistical analysis. Narrowing the identified gap by statistically analyzing related empirical data is the point of departure of this study.

Research Questions, Data Collection, and Methodology

The overarching objective of this study is to empirically examine the patterns of market concentration in U.S. construction industry since the COVID-19 pandemic. Market concentration, a term originated from economics, measures the extent to which market shares are concentrated between a small number of firms. In this study, market concentration is indicated by the revenues of companies. To achieve this objective, the study proposes two specific research questions: (1) Whether the revenue gap between giant U.S. construction companies and others is widened, when it is compared to the period before the pandemic? and (2) Whether the market positions (measured by revenue rankings) of U.S. construction companies are consolidated, when they are compared to the period before the pandemic? The disruption by the pandemic will be compared with the counterpart by the Great Recession, which lasted from December 2007 to June 2009 in the U.S. (Rich 2013), to gain insights on the ongoing crisis.

The data used in this study come from Engineering News-Record (ENR) Top List – Contractors. Every year, the list ranks largest U.S.-based general contractors based on their annual revenue in the year before. The rankings, together with the news and cost indices by ENR, have been widely applied in studies published on well-recognized construction journals (e.g., Ashuri and Lu 2010, Liang et al. 2022, and Vashani et al. 2016). The ranking data used in this study cover top 100 companies from 2005 to 2022, which reflect their corresponding annual revenues from 2004 to 2021. The dataset has 1,800 observations (= 100 companies × 18 years), and each observation contains the company name, ranking of the year, and the revenue of previous year. The rationale of using "top 100" is threefold. First, that is a well-established tradition of company ranking (e.g., Forbes 100). Second and more importantly, the use of top 100 companies can satisfyingly serve the research objective – exploring whether the gaps between construction giants (i.e., those well-known companies occupying enormous market shares) and others are widening. As shown in Table 1, the revenues of the 100th companies have always been relatively negligible, compared to the 1st companies. Even though the names of first-ranked companies are familiar to most construction professionals, the names of 100th companies are probably unheard. Therefore, it is reasonable to claim that the involvement of top 100 has covered both "giants" and "others". This empirical evidence is aligned with the Law of Proportionate Effect – a classic principle established by Gibrat (1931) – claiming that the typical size-distribution of firms is positively skew, with a few large firms and many other firms. Furthermore, the results in Table 1 echo the results of another recent study: Coughran (2019) sampled 363 industrial and nonresidential U.S. construction companies ranging from $1 million to over $1 billion in revenue. Goughran found that 51.4 percent of those firms are in the ninth or tenth decile, earning less than $100 million per year. Third and practically, although there are indeed a number of companies smaller than the 100th companies, such as some local firms, their revenues are hard to track and validate. Therefore, a cutoff of 100 can provide sufficient data to examine if the gap between giants and other construction companies is enlarged.

Table 1

Relative sizes of the 100th companies to the 1st companies – descriptive statics from 2004 to 2021

Median	**Average**	**Maximum**	**Minimum**
3.10%	3.64%	6.88%	1.98%

The following research steps were adopted to achieve research objectives:

1. (For research objective#1) Fitting a Pareto distribution to the revenue and ranking data. The relationships between the size of a company and the ranking of a company have been found generally approximating the Pareto distribution, as denoted by Equation (1) (Hart 1962).

$$\log S = a + b \cdot \log R \qquad \text{Equation (1)}$$

where S is the size of a company measured by revenue, and R is the ranking of a company in order of size. The coefficient b is the Pareto coefficient, which is an indication of the gap between different companies: a larger absolute value of b means that the revenue gap between two companies with consecutive rankings is greater and the market is more concentrated.

2. (Step 2 to Step 4 are for research objective#2) Calculating descriptive statistics of the change of ranking from 2005-2022. The change of ranking is denoted by Equation (2)

$$C_{i,j} = \left| i - R_{i,j} \right| \qquad \text{Equation (2)}$$

where $C_{i,j}$ is the change of ranking of an i^{th} company in the year of j, $R_{i,j}$ is the ranking of the same company in the year before. $i \in [1{,}100]$, $j \in [2005{,}2022]$, $i, j \in Z^{+}$. This step illustrates how the patterns of change of ranking (i.e., a measurement of the consolidation of market position) evolve across years.

3. Conducting Shapiro-Wilk normality test, a commonly-used test for univariate normality (Shapiro and Wilk 1965), on the changes of ranking within a same year (i.e., C_{i,j^*}, where j^* is a constant). Normality assumption – the distribution of data within each group (i.e., changes of ranking within a same year in this study) is normally distributed – is a premise of the one-way ANOVA (analysis of variance) to be performed in the next step.

4. Using one-way ANOVA (when normality test passed) or equivalent nonparametric test (when normality test failed) to test if the mean values of the changes of ranking across years are statistically significantly different. This step empirically examines if the changes of ranking during the COVID-19 pandemic demonstrate different patterns. In other words, this step provides statistical evidence on if market positions of construction companies are more consolidated due to the pandemic.

Results and Discussions

Table 2 shows the parametric details of Pareto distribution fitting (i.e., research step#1). The values of adjusted R^2 and p-values confirm the strong explanatory capability of Pareto distribution in terms of the relationship between the size of a company (measured by revenue) and the ranking of a company. The revenue gap between construction companies, measured by the absolute value of b (a dimensionless quantity), is as shown in Figure 1.

Table 2

Pareto distribution fitting of the relationships between a company's revenue (2004-2021) and ranking (2005-2022)

Year (by revenue)	$\boldsymbol{a}$	$\boldsymbol{b}$	**Adjusted** $\boldsymbol{R^2}$	**p-value**	**Note**
2021	4.51	-0.74	0.95	$< 2.2 \times 10^{-16}$	The period of COVID-19
2020	4.48	-0.73	0.96	$< 2.2 \times 10^{-16}$	
2019	4.50	-0.75	0.97	$< 2.2 \times 10^{-16}$	The pre-pandemic era
2018	4.52	-0.77	0.98	$< 2.2 \times 10^{-16}$	
2017	4.50	-0.78	0.98	$< 2.2 \times 10^{-16}$	
2016	4.50	-0.79	0.99	$< 2.2 \times 10^{-16}$	
2015	4.52	-0.82	0.99	$< 2.2 \times 10^{-16}$	
2014	4.58	-0.88	0.99	$< 2.2 \times 10^{-16}$	

2013	4.59	-0.90	0.99	$< 2.2 \times 10^{-16}$	
2012	4.54	-0.88	0.98	$< 2.2 \times 10^{-16}$	
2011	4.51	-0.88	0.99	$< 2.2 \times 10^{-16}$	
2010	4.49	-0.90	0.99	$< 2.2 \times 10^{-16}$	
2009	4.59	-0.94	0.98	$< 2.2 \times 10^{-16}$	The Great Recession
2008	4.56	-0.86	0.98	$< 2.2 \times 10^{-16}$	
2007	4.45	-0.81	0.97	$< 2.2 \times 10^{-16}$	
2006	4.40	-0.83	0.97	$< 2.2 \times 10^{-16}$	The pre-recession period
2005	4.41	-0.89	0.98	$< 2.2 \times 10^{-16}$	
2004	4.36	-0.88	0.99	$< 2.2 \times 10^{-16}$	

* This column will be 2005-2022 if it was by rank. Because the ranking of a certain year is based on the revenue of the previous year (e.g., the ranking of 2022 is based on the annual revenue of 2021).

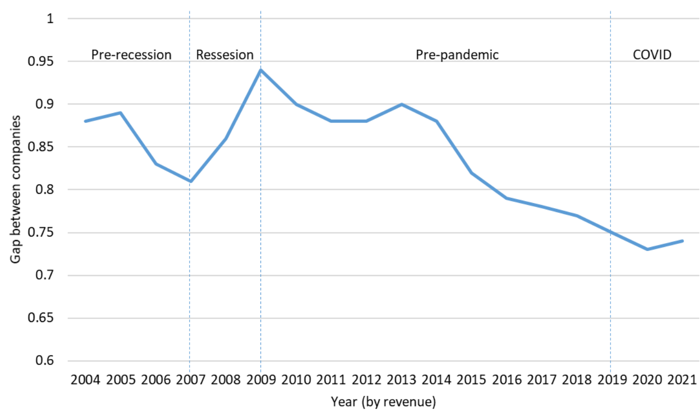

Figure 1 Revenue Gap between Construction Companies from 2004 to 2021

As shown in Figure 1, the revenue gap between construction companies was enlarged by around 116% during the Great Recession. During the period before recession (i.e., 2004-2007) and the period after the recession (i.e., 2010-2019), the revenue gap was narrowed by around 4%/year and 2%/year, respectively. As to the U.S. COVID-19 timeline, the first lab-confirmed case happened in January 2020, and the first shutdown happened in March 2020. Until the end of 2020, most States in the U.S. had lifted their shutdowns (CDC 2022). During 2020, the first year of the pandemic, the revenue gap between construction companies continued the previous decreasing trend with a rate of around 3%/year. In the second year (i.e., 2021), the revenue gap stopped going downwards and rose slightly by 1%. However, it is too early to call that the pandemic reverses the narrowing trend of revenue gaps. Current empirical evidence can confirm that until two years after the outbreak of the COVID-19 pandemic, there is not yet an obvious disruption to the revenue gap between construction companies. This is very different from the last crisis – the Great Recession.

Table 3, Figure 2, and Figure 3 show the results of research step#2 and #3. Since the normality assumption was rejected, Kruskal-Wallis (K-W) test – a non-parametric equivalence of one-way ANOVA – was performed on the 18 groups of change of ranking (i.e., 2005-2022). Corresponding to research step#4, the K-W test examines whether samples originate from the same distribution (Kruskal and Wallis 1952). The results of K-W test fail to reject the null hypothesis – the medians of all groups are equal. The details of K-W test are shown in Table 4.

The medians of ranking change across years generally remain stable, even during the Great Recession and the COVID-19 pandemic. The mean of medians is 5.25 out of 100. Compared to the Great Recession period, the mean value of ranking change and the standard deviation of ranking change are less during the pandemic, which implies the market positions of construction companies are generally more consolidated. This statement can also be supported by less large outliers in terms of ranking change during the pandemic (Figure 2).

Table 3

Descriptive statistics and normality test of the changes of rank from 2005 to 2022 (SD = standard deviation, S-W = Shapiro-Wilk)

Statistics	**Year**								
	2022	**2021**	**2020**	**2019**	**2018**	**2017**	**2016**	**2015**	**2014**
Mean	7.81	9.37	13.89	12.67	9.30	8.88	8.30	9.87	10.17
Median	5	6	9	4	5	4	5	6	5
SD	8.02	13.65	14.58	22.84	10.59	11.20	9.27	11.64	18.54
S-W*	$1*10^{-9}$	$3*10^{-15}$	$1*10^{-9}$	$1*10^{-15}$	$1*10^{-10}$	$1*10^{-11}$	$1*10^{-10}$	$3*10^{-11}$	$2*10^{-16}$
	2013	**2012**	**2011**	**2010**	**2009**	**2008**	**2007**	**2006**	**2005**
Mean	10.98	12.27	9.28	13.34	15.55	11.82	12.21	10.13	8.67
Median	5	5	4	7	6	4.5	5	4	5
SD	17.28	23.89	12.76	18.73	37.23	35.93	18.30	21.71	13.37
S-W	$7*10^{-15}$	$2*10^{-16}$	$3*10^{-13}$	$4*10^{-13}$	$2*10^{-16}$	$2*10^{-16}$	$5*10^{-14}$	$2*10^{-16}$	$8*10^{-15}$

*The null hypothesis of S-W test is the data is normally distributed. The minimal value of S-W test that can be calculated is $2*10^{-16}$

Overall, the COVID-19 pandemic has not yet brought obvious shocks, neither increase or decrease, to the revenue gap between U.S. construction companies and suggests a more consolidated profile of market positions. That constitutes a sharp contrast with the Great Recession, which enlarged the revenue gap and triggered more position changes. According to the Federal Reserve Bank (Şahin et al. 2011), there is a disproportionate relationship between the decline during the Great Recession and the size of company. The smaller the company, the more significant difficulties in raising funds for regular operations or new investments may occur. Compared to the companies which have more diversified sources of financing, companies smaller in size tend to heavily rely on bank loans. For instance, the balance-sheet data surveyed by the Federal Reserve Bank of New York show that bank loans account for 2/3 of the total debt of small companies, while the number is ¼ for large companies. And bank loans declined significantly since the start of Great Recession. The study by the Federal Reserve Bank further points out that the Great Recession leads to shrunk total needs, which exaggerates the existing disadvantaged status in competitions of many companies. However, the COVID-19 pandemic suggests a very different context. First, the Coronavirus Aid, Relief, and Economic Security (CARES) Act became law in March 2020. As one of the key provisions, the Paycheck Protection Program (PPP) managed by the U.S. Small Business Administration provided $669 billion in assistance, with 90% of the funds allocated by the first week of May 2020 (Kapinos 2021). Furthermore, the 1.2 trillion Infrastructure Investment and Jobs Act became law in November 2021, which can be dated back to the American Jobs Plan first proposed in March 2021. The massive infrastructure investment plan suggests a very different scenario in terms of the confidence to U.S. construction market compared to the days during the Great Recession. Nevertheless, it is worthy to note that current empirical evidence can only support statements on the impacts until the beginning of 2022. It is too early to examine the long-term impacts of the COVID-19 pandemic on the revenue gap between U.S. construction companies and to evaluate the effectiveness of government interventions.

The vibrant merger-and-acquisition activity in U.S. construction industry since 2010 helps giant construction companies consolidate their market positions and can explain the stable ranking changes across years. Giant construction companies tend to become more competitive after merging smaller but capable competitors. The activity slowed down during the Great Recession as a result of paralysis over business climate and resumed again afterwards (Rubin 2010). The suspension of merger-and-acquisition paused the consolidation and brought more changes of market positions. However, the current crisis suggests a context different from the Great Recession: in addition to the stimulus to infrastructure sectors, the housing market remains hot during the pandemic (Florida 2022).

Table 4

Results of Kruskal-Wallis test with the null hypothesis that the medians of all groups are equal

Chi-squared	**Degree of freedom**	**p-value**
17.28	17	0.44

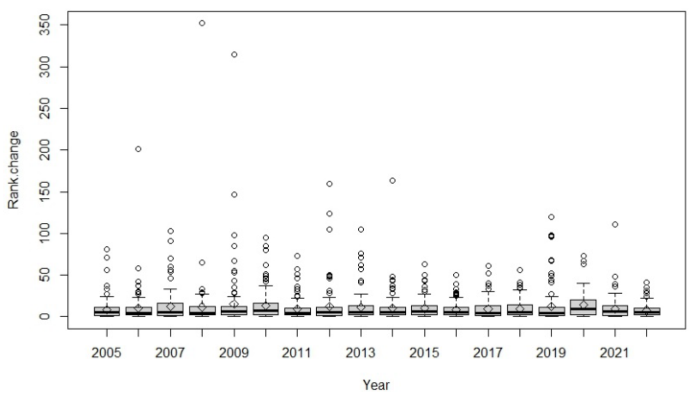

Figure 2 Boxplot of change of ranking from 2005 to 2022 (original plot)

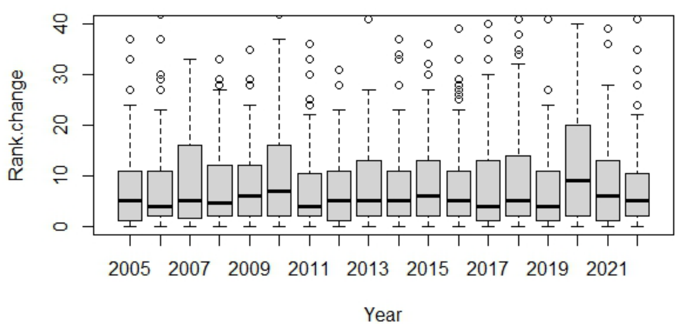

Figure 3 Boxplot of change of ranking from 2005 to 2022 (outlier-removed)

Conclusions and Future Works

This study responds to the concerns if the U.S. construction industry is more consolidated since the COVID-19 pandemic. Both absolute revenue (measured by U.S. dollar) and relative revenue (measured by revenue ranking) were examined, using the data from ENR. The results of statistical analysis show that until the beginning of 2022, no obvious disruptions on the evolvement of revenue gap have incurred. Over the past 18 years (including the pandemic period), the revenue gap between U.S. companies generally narrows except the period of the Great Recession. The analysis also shows that the change of ranking across years generally remains stable, despite the higher volatility during the Great Recession. The impacts of the two crises, i.e., the pandemic and the Great Recession, on the market concentration of the U.S. construction industry are very different. By comparatively analyzing the natures of the two crises with focuses on their impacts to the U.S. construction industry, the study argues that government interventions are generally effective stabilizers, until the cutoff for data collection in this study, i.e., the beginning of 2022.

The future works can be continued from two aspects: First, longitudinal data before 2004 and longitudinal data since 2022 need to be involved. Currently, the pre-recession period only contains the data from four years, and the COVID period only contains two-year data. The period of post-COVID has not yet been constructed. Extended length of study can be expected to generate more robust results. Second, the industry sector (e.g., transportation, industrial, and power) needs to be included as an explanatory variable. The levels of market concentration of various industry sectors are different. For instance, in 2021, top 20 transportation general contractors account for 56.4% of the total revenue of top 400 transportation general contractors. The numbers are 82.6%, 73.5%, 96.9%, 92.2% for the power sector, the industrial sector, the petroleum sector, and the telecommunication sector, respectively (ENR 2022). The inclusion of industry sector can generate more specified results on the pattern of market concentration.

References

AIA Group. 2020. March 2020 Special Report: Moving ahead, challenging times confront the design professions (Issue April).

Ashuri, B., and Lu, J. 2010. “Time Series Analysis of ENR Construction Cost Index” *Journal of Construction Engineering and Management*, 136(11): 1227-1237.

BAE (Bureau of Economic Analysis). 2022. *Gross Domestic Product, Second Quarter 2022*

Biörck, J., Sjödin, E., Blanco, J. L., Ribeirinho, M. J., & Rockhill, D. 2020. How construction can emerge stronger after coronavirus. McKinsey & Company.

Bistrova, J., Lace, N., & Kasperovica, L. 2021. “Enterprise Crisis-Resilience and Competitiveness.” *Sustainability*, 13(4): 2057.

Bloom, N. 2017. *Corporations in the Age of Inequality.* Harvard Business Review.

CDC (Centers for Diseases Control and Prevention) 2022. *CDC Museum COVID-19 Timeline*

Coughran, S. 2019. *What You Need to Know About the Construction Industry’s Earnings Gap.* Construction Business Owner.

ENR. 2022. *The Top 400.*

Florida, R. 2022. “How the ‘Rise of the Rest’ Became the ‘Rise of the Rents’” Bloomberg.

Gibrat, R. 1931. *Les Inégalités économiques*, Paris.

Govindarajan, V., Lev, B., Srivastava, A., & Enache, L. 2019. *The Gap Between Large and Small Companies Is Growing. Why?* Harvard Business Review.

Hart, P.E. 1962. "The Size and Growth of Firms" Economica, New Series, 29(113): 29-39.

Kapinos, P. 2021. *The Paycheck Protection Program: Conditional Success or Unconditional Failure?* Federal Reserve Bank of Dallas.

Karakaplan, M.U. 2021. "This time is really different: The multiplier effect of the Paycheck Protection Program (PPP) on small business bank loans" *Journal of Banking & Finance*, 133:106223.

Kruskal, W.H., and Wallis, W.A. 1952. "Use of ranks in one-criterion variance analysis". *Journal of the American Statistical Association*, 47(260): 583–621.

Liang, Y., Baral, A., Shahandashti, M., and Ashuri, B. "Availability Heuristic in Construction Workforce Decision-Making amid COVID-19 Pandemic: Empirical Evidence and Mitigation Strategy" *Journal of Management in Engineering*, 38(5): 04022046

Obando, S. 2022. *Did the US just sink into a recession? ABC Chief Economist Anirban Basu predicts next year to be fraught with risk.* ConstructionDive.

Phillips, Z., & Bousquin, J. 2021. *Fluor's revenue falls, Granite posts gain.* Construction Dive.

Rich, R. 2013. *The Great Recession*, Federal Reserve Bank, Cleveland, Ohio

Rubin, D.K. 2010. "Industry Merger-and-Acquisition Activity Is Gaining Steam" *Engineering News-Record*

Şahin,A., Kitao, S., Cororaton, A., and Laiu, S. 2011. "Why Small Businesses Were Hit Harder by the Recent Recession." *Current Issues in Economics and Finance*, 17(4). Federal Reserve Bank of New York.

Shapiro, S.S. and Wilk, M.B. 1965. "An Analysis of Variance Test for Normality (Complete Samples)" *Biometrika*, 52(3/4): 591-611.

Smallbone, D., Deakins, D., Battisti, M., & Kitching, J. 2012. "Small business responses to a major economic downturn: Empirical perspectives from New Zealand and the United Kingdom." *International Small Business Journal*, 30(7): 754–777.

Tansey, P., Spillane, J. P., & Meng, X. 2014. "Linking response strategies adopted by construction firms during the 2007 economic recession to Porter's generic strategies." *Construction Management and Economics*, 32(7–8): 705–724.

Vashani, H., Sullivan, S.J., and El Asmar, M. 2016. "DB 2020: Analyzing and Forecasting Design-Build Market Trends" *Journal of Construction Engineering and Management*, 142(6): 04016008.

Assessing the Consistency Between the Expected and Actual Influence of LEED-NC Credit Categories on the Sustainability Score

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This study investigates the relationship between the LEED BD+C for New Construction (LEED-NC) scores achieved by projects and their scores from each credit category to assess the consistency between the expected and the actual influence of these credit categories in determining the sustainability of a project. The data was collected about all of the built LEED-BD+C for New Construction projects and the relationships between each credit category and the sustainability level of the projects, defined by LEED scores, were evaluated through multiple linear regression analysis. The findings showed the harmony between the expected and the actual influence of the Energy and Atmosphere category and Sustainable Site category in determining the overall sustainability of the projects. However, the three credit categories of Materials and Resources, Indoor Environmental Quality, and Water Efficiency did not show any harmony between the expected and the actual influence on determining the overall sustainability level of projects. The findings of this study illustrate the need for enhancing the consistency between the existing sustainability evaluation criteria and suggests more comprehensive research on the factors defining the level of sustainability of a project.

Key Words: LEED, Sustainable Site, Energy and Atmosphere, Water Efficiency, Indoor Environmental Quality, Materials and Resources

Introduction

Green building certification systems are developed to enhance the sustainability and efficiency of construction projects. Some factors such as environmental performance, occupant comfort, and human health, which are known as the ultimate goals of any sustainability standard are evaluated through these certification systems. The systems evaluate several aspects of the building life cycle, including design, construction, maintenance, disassembly, energy, raw materials, and pollutant emissions (Kim et al., 2020). Several frameworks and certification systems have been developed to evaluate a building's environmental performance and incorporate sustainable development into the design and construction processes (Ali & Al Nsairat, 2009). One of the most commonly used systems to assess the sustainability of buildings and communities is the Leadership in Energy and Environmental Design (LEED) (Wu et al., 2016). Other than defining a set of criteria for evaluating the performance of buildings, this system has the additional benefit of raising public awareness of environmental preservation, fostering the development of green technologies, boosting green technology research and development, and stimulating green building construction (Kim et al., 2020).

Overview of LEED-NC

In 1998, the USGBC has used LEED standards to evaluate buildings based on their environmental performance. Since then, LEED systems have been updated in light of technological advancements and changes in regulations and policies. The most current version of LEED is version 4.1, which has updated some of the credits of LEED version 4. LEED version 4 was developed in 2013 and significantly changed the number of green building systems. Before version 4, LEED v2009 also known as LEED v3 was the common LEED system. In LEED versions 3 and 4, the projects can gain a total of 110 points based on their compliance with the LEED standards. In this system, if a project gains at least 40 points, it is considered a LEED-Certified project. The next level is the LEED-Silver level, which requires between 50-60 points. LEED Gold is achieved if a project receives between 60-80 points, and, as the highest level of LEED certification, LEED-Platinum is achieved if a project receives at least 809 points (Kim et al., 2019).

Every building construction project can follow the LEED BD+C system by choosing a specialty option or just following New Construction and Major Renovations for all the requirements (U.S. Green Building Council, 2013). The LEED BD+ C has several sub-systems including New Construction and Major Renovation, Core and Shell Development, Data Centers, Healthcare, Hospitality, Retail, Schools, Warehouses and Distribution Centers, and Multifamily Residential systems (U.S. Green Building Council, 2013). Among the sub-systems of LEED BD+C system, the most popular one is LEED for New Construction and Major Renovations (LEED-NC). This system is developed comprehensively in order to satisfy the various needs of different building types (Cheng & Ma, 2015).

LEED-NC version 3 consisted of seven credit categories including Sustainable Sites (25 points), Water Efficiency (10 points), Energy and Atmosphere (35 points), Materials and Resources (14 points), Indoor Environmental Quality (15 points), Innovation (6 points), and Regional Priority (4 points). However, significant changes were made in 2013 when LEED v4 was developed and the credit categories of LEED-NC changed into nine categories. The categories are Sustainable Sites (10 points), Water Efficiency (11 points), Energy and Atmosphere (33 points), Materials and Resources (13 points), Indoor Environmental Quality (16 points), Location and Transportation (20 points), Innovation (6 points), and Regional Priority (4 points). A building can be labeled depending on the LEED (BD+C) points it has received out of a possible 110.

As pointed out, the LEED systems have been updated over time to improve the evaluation criteria by enhancing their applicability. Therefore, it is necessary to study the applicability of this system by assessing the credits earned by the projects to identify the influential and most achievable credits in practice. Hence, in this study, the LEED-NC credit categories are investigated by evaluating the relationships between the credit categories and the overall scores achieved by some of the LEED projects that are similar in terms of the project type. Therefore, this study focuses on university residence halls that are certified under LEED-NC V3 (2009).

Method

Data Collection

In order to collect data from the USGBC website, all the projects having LEED-NC certification were listed. Since the number of LEED-NC projects in the United States is extremely high and the projects can have different purposes, only residence halls were chosen for this analysis to compare similar projects and provide a reliable evaluation. The 149 projects that were identified through the data collection included all the university campus residence halls that are certified under the LEED BD+C for New Construction system in the US by October 25, 2022. Among the 149 projects, the majority of them (n= 93) were certified under version 2009 (v3). The rest of the projects were either v2 or v4 and were removed because the criteria for the certification were different.

After removing the incompatible cases, the data were normalized to make sure that all the variables are using the same scale and providing accurate results. Next, in order to find the influential cases and outliers, the retained 93 cases were entered into a preliminary multiple linear regression (MLR) analysis to test the assumptions for the regression analysis by reviewing the behavior of the residual. As a result, five cases were identified as outliers due to having standardized residuals extremely close to either one or zero, and one project was identified as an influential case due to having a Cook's Distance of greater than 0.05. After removing the outliers and influential cases, 87 projects remained in the model (N= 87) to be considered for the data analysis.

Data Analysis

The dependent variable for this study was the LEED BD+C (NC) score of the projects and the independent variables are "Sustainable Site" (SS), "Water Efficiency" (WE), "Energy and Atmosphere" (EA), "Materials and Resources" (MR), and Indoor Environmental Quality (IEQ). These factors are the main credit categories for certifying a building under LEED BD+C for New Construction in Version 2009. After collecting and preparing the data, the relationship between each of these factors and the LEED score of the projects was assessed through MLR in order to find the independent effect that each of these categories has on the overall sustainability of the project. The findings were then summarized and the relationships were discussed and compared to their roles in determining sustainability as expected in the LEED-BD+C- NC system.

Multiple Regression Assumption Test

The MLR assumptions are lack of multicollinearity, normality of residuals, the linear relationships between each explanatory variable and the response variable, homoscedasticity, and independence of errors (Osborne & Waters, 2002; Gomez et al., 2013; Uyanık & Güler, 2013).

Both the linear relationships and the homoscedasticity assumptions were examined by reviewing the scatterplot of the predicted values of the dependent variable and the standardized residuals (Figure 1).

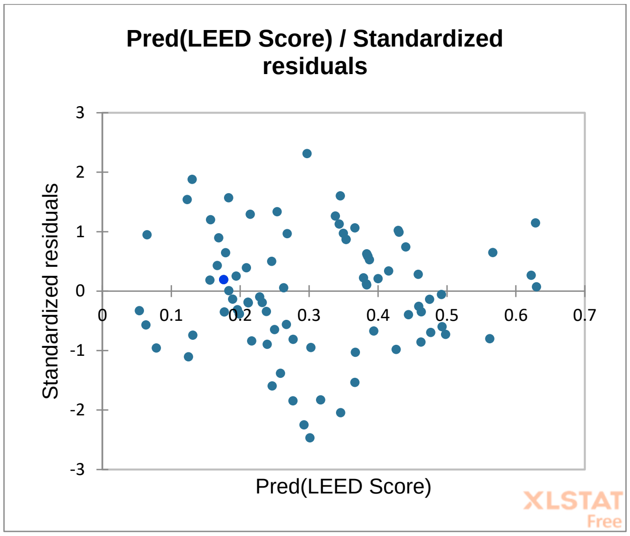

Figure 1. Residual plot

As shown in Figure 1, from the scatterplot it is evident that linear relationships exist between the variables. Furthermore, a lack of any clear pattern in the distribution of the residuals demonstrates the homoscedasticity of the data. The normality of residuals was assessed through a Shapiro-Wilk test (Table 1). The null hypothesis in this test is the normality of the residuals while according to the alternative hypothesis, the residuals are not normally distributed.

Table 1

The normality of residuals (Shapiro-Wilk test)

W	0.992
p-value (Two-tailed)	0.859
alpha	0.050

The p-value of greater than 0.05 shown in Table 2 indicates that the null hypothesis cannot be rejected, thus concluding that the residuals' distribution is normal.

The independence of errors was assessed using the Durbin-Watson test. In this test, the values between 1.5 and 2.5 (close to 2) show no considerable autocorrelation between the residuals. The Durbin-Watson value (Table 2) indicates the independence of errors (DW value = 1.845).

Table 2

Durbin-Watson Test Results

Autocorrelation	Statistic	p
0.163	1.845	0.097

An analysis of Tolerance and the Variance Inflation Factor (VIF) was conducted to test the lack of multicollinearity assumption. The VIF of lower than 10 and the Tolerance of greater than 0.1 indicates that multicollinearity is not an issue among the independent variables.

Table 3

Multicollinearity Test Results

	SS	WE	EA	MR	IEQ
Tolerance	0.860	0.886	0.953	0.961	0.936
VIF	1.162	1.129	1.049	1.040	1.068

Multiple Linear Regression Analysis

After ensuring that regression assumptions are met by the data, the relationships between the sustainability score of the 87 projects and their scores in SS, WE, EA, MR, and IEQ credit categories were evaluated through an MLR analysis (N=87). The descriptive statistics of the MLR analysis are shown in Table 4.

Table 4

Descriptive statistics

Variable	Observations	Obs. with missing data	Obs. without missing data	Minimum	Maximum	Mean	Std. deviation
LEED Score	86	0	86	0.041	0.673	0.310	0.140
SS	86	0	86	0.063	0.875	0.516	0.192
WE	86	0	86	0.000	1.000	0.605	0.248
EA	86	0	86	0.000	0.813	0.279	0.161
MR	86	0	86	0.000	1.000	0.432	0.204
IEQ	86	0	86	0.000	1.000	0.606	0.174

The goodness of fit statistics was first evaluated to understand the amount of variance in the LEED score that is explained by the five credit categories (Table 5). The R square of 0.926 (R2= 0.926) illustrates that the five independent credit categories explain 93% of the variability of the LEED NC Score.

Table 5

Goodness of fit statistics

Observations	86
Sum of weights	86
DF	80
R^2	0.926
Adjusted R^2	0.922
MSE	0.002
RMSE	0.039
MAPE	13.718
DW	1.845
Cp	6.000
AIC	-551.012
SBC	-536.286
PC	0.085

To test the statistical significance of the results, an analysis of variance (ANOVA) was conducted (Table 6). The results showed a statistically significant variance between the model mean and the LEED NC score (DF= 5; F= 201.391, p<.0001).

Table 6

Analysis of Variance

Source	DF	Sum of squares	Mean squares	F	Pr > F
Model	5	1.553	0.311	201.391	**<0.0001**
Error	80	0.123	0.002		
Corrected Total	85	1.677			

Computed against model Y=Mean(Y)

Finally, the standardized coefficient analysis was conducted to evaluate the magnitude and significance of the relationships between the total LEED score and the independent credit categories. According to table 7, the EA category has the strongest influence on the total LEED score (Coefficient=0.795, P-value<0.0001) among all the credit categories. The SS category is the second influential category on the total LEED score of the projects (Coefficient= 0.454, P-value<0.0001) followed by the MR category (Coefficient= 0.353, P-value<0.0001), IEQ category (Coefficient= 0.284, P-value<0.0001), and WE category (Coefficient= 0., P-value<0.0001), which shows the weakest positive influence on the sustainability score among all categories.

Table 7

Standardized coefficients

	Value	Standard error	t	Pr > |t|	Lower bound (95%)	Upper bound (95%)
SS	0.454	0.028	16.333	**<0.0001**	0.399	0.509
WE	0.283	0.031	8.594	**<0.0001**	0.202	0.324
EA	0.795	0.026	30.226	**<0.0001**	0.742	0.847
MR	0.353	0.033	10.570	**<0.0001**	0.287	0.420
IEQ	0.264	0.026	11.030	**<0.0001**	0.233	0.335

Discussion

The findings indicated that among all the studied credit categories, the Energy and Atmosphere category has the strongest influence on the overall LEED score of the projects. This finding was expected as this credit category accounts for 35 points out of 110 total points (32%). This finding supports that the important role that is considered for this credit category is consistent with what the projects have gained in achieving LEED certification. This demonstrates that achieving energy efficiency in buildings is both practical and influential in achieving community sustainability.

The Sustainable Site category was the second category showing a significant influence on sustainability. This category has also been emphasized in the LEED-NC system as a key determinant of sustainability by accounting for up to 26 potential points for improving different aspects related to the project site. Although the findings of this study have supported this important role, it is beneficial to discuss the consistency of this finding with the relevant existing literature and see if the direct and indirect effects of this factor are also consistent with the expected sustainability outcomes.

The Materials and Resources category was the third factor showing an influence on the overall sustainability level of LEED projects in this study. However, this category is the fourth largest credit category in the LEED-NC system in terms of the potentially available credits by accounting for a total of 14 potential credits. Accordingly, water efficiency, which has the lowest number of potential points by accounting for 10 credits in the LEED NC system is following Materials and Resources in this study. Indoor Environmental Quality, on the other hand, showed the lowest influence in determining the sustainability of studied projects while this credit category is the third largest category in the LEED NC system by accounting for 15 potential points.

The discrepancies between the importance of the credit categories from the LEED system standpoint and the influence they have on determining the overall LEED NC scores in practice highlight the need for more studies on the potential impact of these credits on sustainability. It also highlights the fact that the possibility of achieving some of the credits might be lower than others and assigning a high weight for them might not be practical. This might not only discourage the practitioners to attempt toward achieving those points, but it might also provide an unbalanced certification system that does not show internal consistency. Therefore, the Green Building Certification Institute should either change the criteria for achieving these points or reduce the number of points that can be achieved by meeting the current criteria and allocate the remaining points to the credits that are more practically achievable.

Overall, this study demonstrates that the LEED-ND system should reconsider the weighting for some of the factors and redevelop the measures for the evaluation of some credits. Given the points that were discussed in this study, there is a need for further studies that expand the knowledge about the practicability of the LEED-NC criteria and their application in assessing the sustainability level of the projects.

Conclusion

This study evaluated the relationship between the LEED NC score and some of the key credit categories in determining the sustainability of projects. The purpose of the study was to find the harmony between the expected and the actual influence of these credit categories in determining the sustainability of a project. The findings of the study showed some harmony and some inconsistencies. The credit categories of Energy and Atmosphere and Sustainable sites showed the harmony between the expected and actual influences on the overall sustainability level. However, the three credit categories of Materials and Resources, Indoor Environmental Quality, and Water Efficiency did not show any harmony between the expected and the actual influence on determining the overall sustainability level of projects.

The findings highlight the potential need for re-evaluating the criteria under the three categories that did not show consistency between the expected and the actual influence on determining sustainability. The limitation of this study is the number of projects that have been studied for evaluating the relationships between the achieved points and the total sustainability scores. However, as discussed in the introduction, the reason for the limited number of studied cases was that the authors compared the projects with the same use (residence halls) so that the application of the LEED criteria could be comparable and provide a reliable outcome. This limitation provides the opportunity for future research that consider a larger group of similar projects that share common credits for certification.

Reference

Ali, H. H., & Al Nsairat, S. F. (2009). Developing a green building assessment tool for developing countries – Case of Jordan. *Building and Environment*, *44*(5), 1053–1064. https://doi.org/10.1016/J.BUILDENV.2008.07.015

Cheng, J. C. P., & Ma, L. J. (2015). A data-driven study of important climate factors on the achievement of LEED-EB credits. *Building and Environment*, *90*, 232–244. https://doi.org/10.1016/J.BUILDENV.2014.11.029

Kim, J. M., Son, K., & Son, S. (2020). Green benefits on educational buildings according to the

LEED certification. *International Journal of Strategic Property Management*, *24*(2), 83–89. https://doi.org/10.3846/IJSPM.2020.11097

Osborne, J. W., & Waters, E. (2002). Four assumptions of multiple regression that researchers should Four assumptions of multiple regression that researchers should always test always test. *Practical Assessment, Research, and Evaluation*, *8*(2), 2. https://doi.org/10.7275/R222-HV23

U.S. Green Building Council. (2013). *LEED credit library | U.S. Green Building Council*. School of Government and Public Policy. https://www.usgbc.org/credits?Rating+System=%22Neighborhood+Development%22&Version=%22v4%22

Uyanık, G. K., & Güler, N. (2013). A Study on Multiple Linear Regression Analysis. *Procedia - Social and Behavioral Sciences*, *106*, 234–240. https://doi.org/10.1016/j.sbspro.2013.12.027

Williams Carlos Alberto Gomez Grajales Dason Kurkiewicz, M. N., & Alberto Gomez, C. (2013). Assumptions of Multiple Regression: Correcting Two Misconceptions. *Practical Assessment, Research, and Evaluation*, *18*, 11. https://doi.org/10.7275/55hn-wk47

Wu, P., Mao, C., Wang, J., Song, Y., & Wang, X. (2016). A decade review of the credits obtained by LEED v2.2 certified green building projects. *Building and Environment*, *102*, 167–178. https://doi.org/10.1016/J.BUILDENV.2016.03.026

Wu, P., Song, Y., Hu, X., & Wang, X. (2018). A Preliminary Investigation of the Transition from Green Building to Green Community: Insights from LEED ND. *Sustainability 2018, Vol. 10, Page 1802*, *10*(6), 1802. https://doi.org/10.3390/SU10061802

How the COVID-19 Pandemic Affected the U.S. Residential Construction Industry's Labor Workforce: An Analysis of Interior vs. Exterior Trades in three Metropolitan Areas

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The coronavirus disease has plagued the United States beginning in March 2020 and extending to today, leaving everyone uncertain. Governmental shutdowns, the spread of infection, and more than a million deaths have threatened communities and industries. The residential construction industry was not immune to these challenges. In particular, the residential construction industry contributes significantly to the United States' economic health and growth, so it is crucial to understand this industry's adversities during the pandemic. This study aims to understand the residential construction industry's employment differences between different construction trades and different geographical areas pre-COVID-19 and during COVID-19. The geographical areas analyzed were three metropolitan areas in the U.S., including Miami, FL., Los Angeles, CA, and Columbus, OH. Six different trades were analyzed within these three metropolitan areas, consisting of three interior and three exterior trades. The results indicated an employment disparity amongst construction trades across different metropolitan areas. With this information, the residential construction industry may understand which trades and their geographical areas are more susceptible to employment hardships during economic and health downturns.

Key Words: Pandemic, Employment, Residential, Metropolitan Statistical Areas

Introduction

The coronavirus disease, also known as COVID-19, has left its mark not only on our entire world but it has also left a significant impact on the residential sector of the construction industry. COVID-19 was first detected in Wuhan, China, on December 31, 2019, and continued to spread worldwide for several years. As a result, on March 11, 2020, World Health Organization (WHO) declared COVID-19 a global pandemic (WHO Director-General, 2020). A global pandemic is an outbreak of a disease "occurring over a wide geographic area (such as multiple countries or continents) and typically affects a significant proportion of the population." (Merriam-Webster, 2022).

The U.S. residential construction sector averages 3-5% of the gross domestic product. The residential construction includes new construction of multi-family housing and single-family homes, residential remodeling, and the construction of manufactured homes. When this residential investment is combined with the consumption spending on housing services such as rents and utilities, the residential construction sector makes up 15-18% of the GDP (NAHB, 2022). The residential construction sector contributes substantially to the health and growth of the U.S. economy. With residential construction being a prominent participant in the health of the U.S. economy, it is essential to understand precisely how it was affected during the COVID-19 pandemic to help insulate this significant economic contributor from adverse effects from potential future health or governmental industry restrictions (Bauer et al., 2020).

Previous studies have been conducted on construction employment and how COVID-19 has affected the industry (Afkhamiaghd & Elwakil, 2020). Still, no studies have been discovered on the employment rates among specific residential trades during the COVID-19 pandemic. Therefore, this research aimed to answer how the COVID-19 pandemic affected the construction industry employment rates among residential interior and exterior trades in Los Angeles, CA., Columbus, OH., and Miami, Fl. The research questions were:

- Were there differences in the unemployment rates amongst these trades depending on three different metropolitan cities of the United States that would indicate a geographic disparity?
- Did the construction trades show any difference in employment pre-COVID-19 and during COVID-19?
- If there was a difference in employment, did the construction industry trades show resiliency and bounce back?

This study adds to our understanding of how the pandemic hit trades and the most challenging metropolitan areas in the residential construction industry. Based on these answers, there may be a better understanding of if and why different parts of the country are more susceptible to industry interruptions and if specific trades are more resilient to contagious illnesses because of safety measures implemented.

Literature Review

In 2019, the residential construction industry contributed to 4.1% of the total Gross Domestic Product (GDP) in the United States (Biswas et al., 2021). Cities or metropolitan areas hit the hardest during the first wave of the pandemic tended to be those with an international airport and were a global hub for business and travelers, such as Miami, Fl. The less connected areas of the country were hit later by the virus when different control measures were in place (Florida et al., 2021). The pandemic calendars from the New York Times showed Miami, FL, was affected harder with infected individuals than Los Angeles, CA. or Columbus, OH (The New York Times, 2022). In addition to the geographical region contributing to the infection rate, the work type also shaped the spread of the pandemic. As office-based workers typically performed their work from home, the public-facing employees remained more exposed to the virus. The communities most devastated by the COVID -19 virus were the working-age Latinx and African American communities (The Atlantic Monthly Group, 2021). The COVID-19 illness in these communities was attributed to comorbidities, crowd housing, and work patterns. Many individuals in these communities worked in what were deemed essential sectors of the economy. Typically, these individuals did not have the option of working from home. Studies showed that the primary source of exposure to COVID-19 for these employees was their workplace. In many cases, these work environments did not provide sufficient social distancing, personal protective equipment (PPE), or adequate ventilation and sanitation (The Atlantic Monthly Group, 2021).

Safety Measures Implemented

In the U.S., the Occupational Safety and Health Agency (OSHA) ensures safe and healthy working conditions for construction workers by implementing and enforcing health standards. This government agency is a part of the U.S. Department of Labor. OSHA implemented guidelines during the pandemic to help protect individuals from contracting COVID-19 while working in the field. At the onset of the pandemic, there were no vaccines, so other risk mitigations were implemented. The steps suggested by OSHA for employers to keep their workers safe were to make sure sick workers stayed home, implement physical distance by more than 6 ft, keep in-person meetings short, provide and instruct all workers to wear face masks, and wear PPE. If necessary, the employers were instructed to use the Environmental Protection Agency (EPA) approved cleaning supplies to clean tools and machines and ensure that shared working spaces had good airflow (U.S. Dept of Labor, 2020). In addition to these new guidelines, OSHA implemented additional procedures for those working in carpentry, plumbing, heating/ventilation/air conditioning/ventilation, and masonry.

Employment rates

This study looks at how the construction industry's employment rate was affected by COVID-19 amongst six construction trades across three metropolitan areas. Out of the six different trades, three were interior trades, and three were exterior trades. The interior trades were associated with being on the job site after the walls, roof, and windows were in. These essentially would be trades working in an enclosed building. The three interior trades selected were drywallers, plumbing/HVAC, and finish carpentry. The exterior trades were trades that worked on the shell of the building and worked outdoors. The three exterior trades researched in this study were framers, roofers, and masonry. Additionally, these six trades were chosen because they were the trades that were diligent and thorough in reporting employment numbers to the U.S. Bureau of Labor Statistics by providing complete data sets for every quarter. Many other trades did not have consistent and complete data sets that could be used for the research. Since the construction industry is one of the largest contributing industries to the U.S. gross domestic product (GDP), it is important to understand which construction trades were impacted the most due to the virus. Unfortunately, there have not been studies on the different trades and the effect of COVID-19 to date. Still, the thought was that because interior tradespeople work in an enclosed space on the interior of the building, they work side by side with multiple trades. In addition, because they work in less ventilated areas, they would be more affected than contractors working on the exterior of the building, where individuals are naturally more distanced from others and benefit from fresh air.

Methodology

This research aimed to quantify the impact of COVID-19 on the United States residential construction industry. The first step was to conduct a thorough and detailed literature review by collecting relevant articles to obtain knowledge on how COVID-19 impacted the construction industry by using search engines such as Google Scholar, American Society of Civil Engineers (ASCE), Center for Disease Control and Prevention (CDC), World Health Organization (WHO), and the Bureau of Labor and Statistics (BLS). Research questions were then formulated based on the limited research on this topic since it was a constantly changing situation. For example, how has the COVID-19 pandemic affected the construction industry's employment? Which trades had the most significant employment impact during the 15 months before the pandemic consisting of January 2019 – March 2020 and then 15 months after the U.S. deemed this pandemic a national emergency in the duration of April 2020 – June 2021?

Craft labor data was collected from the U.S. Bureau of Labor Statistics (BLS) at the metropolitan statistical area (MSA) geographic level. An MSA is classified as an urbanized area with at least a population of 100,000 (U.S. Census Bureau, 2013). This classification is utilized in craft labor data collection, analysis, and publication for federal agencies such as the BLS. Unfortunately, the nature of reporting during the pandemic to the BLS was inconsistent among different metros and trades, which caused some challenges. Many craft trades at the metropolitan statistical area (MSA) level had incomplete data sets, limiting the study to only those trades and metro areas that had reported consistently during COVID-19. Los Angeles, CA; Columbus, OH; and Miami, FL MSAs were selected as case study locations for this study based on three criteria. First, COVID-19 cases and deaths varied widely across different U.S. cities throughout the pandemic. MSAs were chosen as the geographical level for data collection since the labor, and COVID-19 data would reflect localized conditions. Second, these MSAs were chosen because each is in a different location across the United States, with Los Angeles, CA, on the west coast, Miami, FL, on the east coast, and Columbus, OH, on the northern Midwest. Third, the MSAs were chosen because they had complete data sets for three exterior trades (e.g., framing, roofing, and masonry) and three interior trades (e.g., drywall, plumbling/HVAC, and finish carpentry) for all ten quarters (30) months of the study timeframe from January 2019 to June 2021.

The shutdown and restrictions for the three studied MSAs all deemed residential construction as an essential industry, according to the Department of Homeland Security's Cybersecurity and Infrastructure Security Agency (CISA). In Los Angeles, the orders were revised on April 10, 2020, and were in effect until May 15, 2020. The variance was that all people were ordered to stay in their homes, and businesses needed to stop all operations. The exceptions included essential infrastructure, which included the operation, inspection, and maintenance of the construction of residential buildings and housing. In Columbus, construction was allowed as an exception under the CISA classification of essential sectors and critical trades. This restriction was in place from April 2– May 1, 2020. Finally, Miami had the least governmental restrictions. Florida governor issued specific variances for Miami that allowed open construction sites no matter the building type, and other tradespeople who maintain safety, sanitation, and essential operations to residential structures essential (Foley, 2020).

The North American Industry Classification System (NAICS) is the standardized classification of businesses used by Federal agencies when analyzing or collecting data regarding the U.S. business economy. For instance, the NAICS for construction is labeled as number 23. However, each specific trade has other numbers after the general 23 classifications to further classify them. For instance, for the residential framing contractors, the number is 238131; residential masonry contractors are 238141; residential roofing contractors are 238161; residential plumbing and HVAC contractors are 238221; residential drywall contractors are 238311; and residential finish carpentry contractors are 238351(BLS, 2020). These numbers were then used to look up data in the Quarterly Census of Employment and Wages (QCEW). The QCEW receives a Quarterly Contribution Report (QCR) from private-sector employers. The collected data was the monthly employment rates for each trade in each MSA area from January 2019 through June 2021(BLS, 2022).

The results from the QCEW were collated in Excel, and a Mann-Whitney statistical analysis was performed. This two-tail t-test test was the recommended standard for data where normality cannot be presumed (Streiner, 2015). The Mann-Whitney test was performed in Excel using XLSTAT. This test is a non-parametric test where two independent samples can be compared. Microsoft Excel (XLSTAT) was used to conduct the Mann-Whitney U test, as shown in Equation 1.

$$U\ stat = Rank\ Sum - [n\ (n - 1) / 2] \quad (1)$$

Two groups were determined to be significantly different using the significance level = 0.05. The pre- and during-COVID-19 employment rates were compared using equal sample sizes. The 15 months of employment before COVID-19 were determined to be January 2019 – March 2020, when the U.S. classified COVID-19 as a national emergency. The second sample was from the following 15 months April 2020 to June 2021.

Results and Discussion

Results of this study highlight changes in residential contractor employment rates before and after COVID-19 across three metropolitan areas – Miami, FL; Columbus, OH; and Los Angeles, CA. Tables 1, 2, and 3 illustrate the Mann-Whitney t-test results comparing the 15 months of pre-COVID-19 with 15 months of active COVID-19. In addition, a two-sample t-test was performed to determine whether the employment during the 15 months before COVID-19, consisting of January 2019 to March 2020, and 15 months during COVID-19, including from April 2020 to June 2021, was significantly different. As illustrated in these tables, if the p-value is less than 0.05, the residential trade showed a significant change in employment during COVID-19. The mean in the tables represents the number of employees. In these tables, the negative employment change is indicated with a negative symbol (-), with the **bold numbers** showing a significant negative employment change from pre-COVID-19 to during COVID-19. Conversely, the positive sign indicates a positive change in employment, and the **bold numbers** demonstrate a significant positive employment change from pre-COVID-19 to during COVID-19.

Table 1 shows varied results within the trades in Miami, FL. These results showed a significant negative difference in employment between the pre-COVID-19 months and the COVID-19 months, with p-values below 0.05 among the framing contractors, roofing contractors, and masonry contractors and a significant increase in employment for the plumbing/HVAC contractors. On the other hand, drywall and finish carpentry contractors showed no significant difference.

Table 1

Differences in Residential Employment in Miami, FL.

Contractor	Before Pandemic (Jan 2019 – May 2020)		After Pandemic (Apr 2020 - Jun 2021)		*P-value*	Trade Type	Employment Change
	Mean	SD	Mean	SD			
Framing	825	79	707	44	**<0.0001**	Exterior	**(-) 1,760**
Roofing	5,489	116	5,203	183	**<0.0001**		**(-) 4,293**
Masonry	1,238	98	1,025	48	**<0.0001**		**(-) 3,185**
Drywall	1,759	70	1,723	59	0.170	Interior	(-) 536
Plumbing /HVAC	13,238	309	13,455	311	**0.015**		**(+) 3,245**
Finish Carpentry	4,007	57	4,021	161	0.170		(+) 205

Table 2 shows the results for residential contractors in Columbus, OH, indicating a significant positive difference in employment from pre-COVID-19 to during COVID-19: the framing contractors, the roofing contractors, the drywall contractors, and the plumbing/HVAC contractors. The masonry and finish carpentry contractors showed no significant change in employment. The critical outcome of this study was how resilient the metropolitan area of Columbus, OH was during COVID-19. All six of the residential construction trades had an increase in employment, and four of those trades had significant positive employment results. This finding could be possible due to Ohio being more insulated in the mid-northern U.S. Also, better education and vaccines were being implemented when the virus reached the middle of the U.S. The increase in employment for all trades might also result from the construction lag. The lag and the low-interest rates for residential construction may have lent themselves to the rise in the residential construction industry in that MSA.

Table 2

Differences in Residential Employment in Columbus, OH.

Contractor	Before Pandemic (Jan 2019 – May 2020)		After Pandemic (Apr 2020 - Jun 2021)		*P-value*	Trade Type	Employment Change
	Mean	SD	Mean	SD			
Framing	74	7	89	3	**<0.0001**	Exterior	**(+) 218**
Roofing	464	31	514	44	**0.001**		**(+) 761**
Masonry	268	41	277	36	0.662		(+) 137
Drywall	499	21	533	28	**0.002**	Interior	**(+) 510**
Plumbing /HVAC	3,022	88	3,256	125	**<0.0001**		**(+) 3,516**
Finish Carpentry	400	13	422	16	**0.000**		**(+) 325**

Los Angeles' masonry contractors, plumbing/HVAC contractors, and finish carpentry contractors had a significant negative difference in employment, as shown in Table 3. Whereas framing, roofing, and drywall contractors had no significant change in employment. Los Angeles metropolitan area had altering results in employment among the different trades.

Table 3

Differences in Residential Employment in Los Angeles, CA.

Contractor	Before Pandemic (Jan 2019 – May 2020)		After Pandemic (Apr 2020 - Jun 2021)		*P-value*	Trade Type	Employment Change
	Mean	SD	Mean	SD			
Framing	4.353	314	4,459	231	0.217	Exterior	(+) 1,582
Roofing	3,430	188	3,346	139	0.054		(-) 1,260
Masonry	2,501	119	2,329	85	**0.000**		**(-) 172**
Drywall	7,362	242	7,497	316	0.217	Interior	(+) 2,024
Plumbing /HVAC	21,064	335	20,246	700	**<0.0001**		**(-) 12,273**
Finish Carpentry	4,644	85	4,476	201	**0.026**		**(-) 2,517**

In Los Angeles, the framing and roofing trades did not see a significant change in employment. However, mason, finish carpentry, and plumbing/HVAC contractors significantly negatively affected employment during COVID-19. These were surprising results since the other two metropolitan areas had a positive increase in employment for both plumbing/HVAC contractors and finish carpentry contractors. Maybe these contractors were more exposed because they were in enclosed buildings, were not able to socially distance the 6ft, did not have adequate ventilation, did not have enough PPE, or because their work tasks overlapped, so all three of these trades could have been in the buildings at the same time leading to more exposure.

The original research hypothesis was that the interior trades' employment would be more significantly affected by COVID-19 than the exterior trades since exterior workers have more room to distance themselves socially. This hypothesis may have proven correct for the most part for the Columbus, OH, and Los Angeles, CA MSAs. However, the Miami, FL MSA results were unexpected, with the exterior trades being the most negatively affected. A potential reason for this might be that Florida's construction industry, no matter what type of building, was exempt from shutdowns (Foley, 2020). The lack of governmental restrictions in Miami might explain why all three exterior trades were significantly negatively affected by employment after COVID-19 hit. Without restrictions and monitored guidelines, the trades may have been in closer and more frequent contact with each other. Another explanation may be that the exterior trades require more crew members, increasing the virus's risk. For example, the roofers, framers, and masons rely on a multiple-person crew to construct walls, install roofs, mortar, and stone walls, etc. These tasks cannot be completed by a one- or two-person crew. Florida was also known for their residents not complying with safety measures as much as the rest of the country. If safety measures such as social distancing, masking, and hand washing frequently were not enforced, then this might explain why these trades were affected.

Although all or some of these factors may have played a role in the unexpected findings in Miami, it seemed evident that an important factor to investigate might be the lower socio-economic classes. The lower socio-economic classes were shown to have been the most affected by the pandemic, and exterior trade workers are more likely to be classified as low-income (Bauer et al., 2020). Low-income workers are also more likely to live in multi-family households that produce more exposure to the virus. In addition, individuals in this class typically had jobs that did not provide the ability to telework which may have lent itself to more exposure for these individuals (Hershbein & Holzer, 2021). Still, one of the main ideas that were sparked by this research was that there should be more studies on how the pandemic affected the socio-economic classes. Typically, these exterior trades in Miami are employed with individuals from a lower socio-economic class. Previous studies discovered that the virus impacted the lower socio-economic classes and the secondary effects the virus caused (Bauer et al., 2020).

In contrast to the exterior trades of Miami, the interior trades of drywallers and finish carpenters in Miami did not have a significant change which may be attributed to the fact that with both trades, they are typically the only trades in the home during their scheduled construction time. Therefore, they may not have been exposed to many people, limiting their risk of contracting the virus. Another layer of protection for the drywallers is that even before COVID-19, drywallers typically wore N95 masks during some of their duties of mudding and spraying texture. This practice adds a layer of protection from the virus. It may explain why the drywaller contractors were the only trade in all three metropolitan areas with no adverse change in employment, only a significant positive change.

Figures 1 and 2 give a more visual understanding of what happened with employment during the 15 months before and during COVID-19 among the three MSAs with the masonry contractors and the drywall contractors. The drywall contractors stayed consistent, but the masonry tells a different story, and it is evident there was a significant decrease in the spring of 2020.

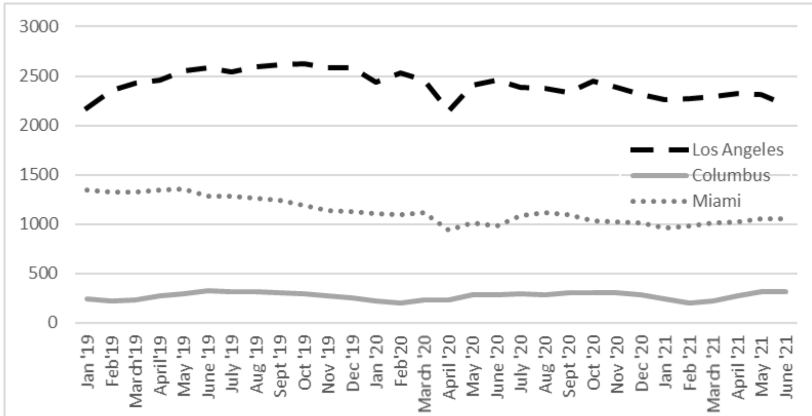

Figure 1. Masonry Employment from Jan 2019 to June 2021

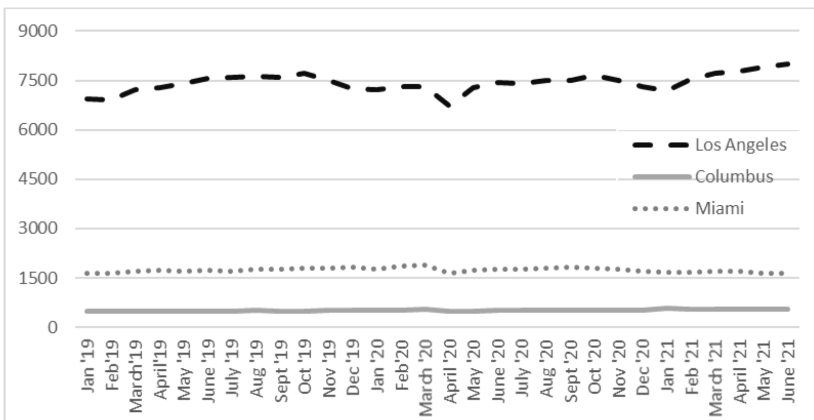

Figure 2. Drywallers Employment from Jan 2019 to June 2021

Conclusion

This research offers insight into the impacts of the COVID-19 pandemic on the residential construction industry. Research findings indicate that the residential construction industry in Columbus, OH, was resilient and thrived in that region throughout the pandemic. Four of the trades even showed a significant increase in employment. In addition, the trades did show a difference in employment pre-COVID-19 and during COVID-19. However, there was no consistency in the interior trades being more negatively affected by employment than the exterior trades. Although the results did not correlate between exterior and interior trades, they correlated to regions. All the trades had significant employment changes in at least one city; however, they were not always negative.

Some significant positive changes indicated the strength and resilience of the residential construction industry in some geographical regions. This positive change would answer the question of a difference in employment rates and show a geographic disparity. Lessons learned in this research was that geography seemed to play a critical role in employment rates during COVID-19. Another lesson learned was that an important factor not involved in this research study that should be considered in future studies would be the impact of socioeconomic classes and COVID-19. The coastal areas of the U.S. were hit faster and harder with the virus than the interior areas studied in this research, and the employment rates reflected corresponding results. The coastal cities of Miami and Los Angeles were affected with more infection rates and unemployment as opposed to the interior urban areas such as Columbus, OH, where not only did the residential construction trades survive during the pandemic, they thrived. This research is vital to help industry members understand which construction trades are more vulnerable to employment hardships during health and economic downturns in our society. This study also shed light on different geographic regions and construction trades that were able to thrive with employment during the pandemic and suffered from loss of jobs.

References

Afkhamiaghd A, M., & Elwakil, E. (2020). Preliminary modeling of Coronavirus (COVID-19) spread in the construction industry. *Journal of Emergency Management (Weston, Mass.)*, *18*(7), 9–17. https://doi.org/10.5055/jem.2020.0481

Bauer, L., Broady, K., Edelberg, W., & O'Donnell, J. (2020, September 17). Ten Facts About COVID-19 and the U.S. Economy. https://www.hamiltonproject.org/papers/ten_facts_about_covid_19_and_the_u.s_economy

Biswas, A., Ghosh, A., Kar, A., Mondal, T., Ghosh, B., & Bardhan, Dr. P. K. (2021). The impact of COVID-19 in the construction sector and its remedial measures. *Journal of Physics: Conference Series*, *1797*(1), 012054. https://doi.org/10.1088/1742-6596/1797/1/012054

BLS. (2020, June 1). *About the U.S. Bureau of Labor Statistics: U.S. Bureau of Labor Statistics*. https://www.bls.gov/bls/infohome.htm

BLS. (2022, August 19). *QCEW Classifications: U.S. Bureau of Labor Statistics*. https://www.bls.gov/cew/classifications/

Florida, R., Rodríguez-Pose, A., & Storper, M. (2021). Cities in a post-COVID world. *Urban Studies*, 004209802110180. https://doi.org/10.1177/00420980211018072

Foley. (2020, April 17). *How Coronavirus Is affecting the Construction Industry: An evolving tracker of Construction Shutdowns Across the United States* [Https://www.foley.com/-/media/files/insights/publications/2020/04/how-coronavirus-is-affecting-the-construction-indu.pdf].

Hershbein, B. J., & Holzer, H. J. (2021). *The COVID-19 Pandemic's Evolving Impacts on the Labor Market: Who's Been Hurt and What We Should Do*. W.E. Upjohn Institute. https://doi.org/10.17848/wp21-341

Merriam-Webster. (n.d.). Pandemic. In *Merriam-Webster.com dictionary*. Retrieved October 30, 2022, from https://www.merriam-webster.com/dictionary/pandemic

NAHB. (2022). *Housing's Contribution to Gross Domestic Product*. Housing's Contribution to Gross Domestic Product. https://www.nahb.org/news-and-economics/housing-economics/housings-economic-impact/housings-contribution-to-gross-domestic-product#

Streiner, D. L. (2015). Statistics Commentary Series: Commentary# 12—One-Tailed and Two-Tailed Tests. Journal of Clinical Psychopharmacology, 35(6), 628-629.

The Atlantic Monthly Group. (2021, May 7). *The COVID Racial Data Tracker*. The COVID Tracking Project. https://covidtracking.com/race

The New York Times. (2022, October 13). *Coronavirus in the U.S.: Latest Map and Case Count*. Https://www.Nytimes.com.

United States Census Bureau. (2013, March 14). *Metropolitan Areas*. https://www2.census.gov/geo/pdfs/reference/GARM/Ch13GARM.pdf

U.S. Dept of Labor. (2020, May 26). U.S. Department of Labor's OSHA Issues Guidance to Help Construction Workers During the Coronavirus Pandemic. https://www.osha.gov/news/newsreleases/national/05262020

WHO Director-General (Director). (2020, March 11). *Media briefing on COVID-19*. https://www.who.int/director-general/speeches/detail/who-director-general-s-opening-remarks-at-the-media-briefing-on-covid-19---11-march-2020

Making, Curing, and Testing Concrete Cylinders in a Senior Level Construction Management Course

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There are few studies which expand upon construction management pedagogical content to guide professors, especially new professors, in the creation and development of hands-on labs. This paper is a case study adding to the construction management body of knowledge to show engineering and construction management educators a framework on how laboratory exercises for making, curing, capping and testing concrete compression cylinders, based on the American Society for Testing and Materials (ASTM) procedures, were developed and incorporated into a senior level construction management course. Included is a course history, description of the laboratory space and equipment and discussion of how the laboratory exercises relate to student learning. Numerical and graphical results of testing concrete cylinders at four different water-to-cement ratios are presented and discussed. Also, future opportunities for similar hands-on student laboratory exercises are identified and discussed.

Key Words: Concrete, Laboratory, Teaching Methods, Lab Exercises

Introduction

Creating a hands-on concrete laboratory is a challenging process to help students understand the essential properties found in a building material that is most widely used in construction. Students in the Construction Management program at Central Washington University (CWU) have a choice of two curriculum options: General Construction, which focuses primarily on building construction or Heavy-Civil Construction, which focuses mainly on roads, bridges, and utility construction. Regardless of the two tracks, all students are introduced the basic concepts of making, curing, and testing concrete cylinders for concrete placement applications whether for a building or bridge. Both courses are taught parallel to each other includes a required eleven-week four-credit (quarter system) senior level course entitled Concrete Construction for the General Construction and Asphalt and Pavement Design for the Heavy-Civil Construction students. The courses emphasize using concrete as a building material and managing concrete projects, as opposed to reinforced concrete design commonly found in engineering focused courses. These courses are not engineering design courses in concrete, but more of the management and understanding in the mechanical properties of concrete that are commonly found in a construction field operation utilizing concrete as a building material.

Literature Review

The laboratory exercises associated with the concrete construction course were developed to create an active learning environment, which has been found to be effective for most construction management students. Research at other institutions offering degrees in construction management indicates that construction students tend to be visual and hands-on learners (Arumala, 2002; Grier & Hurd, 2004). In 1999 a Midwestern university surveyed 73 undergraduate construction management students, mostly juniors and seniors, to better understand their personality types and learning style. Students were categorized by 16 different Myers-Briggs personality types. They were further separated into four simplified temperament groups. It was found that 75% of the students had a sensing/judging temperament and these students like to reach conclusions following a step-by-step approach and put what they have learned to use. It was also discovered that 67% of the students preferred hands-on learning (Stein & Gotts, 2001).

Offering an active learning concrete laboratory experience in a four-year construction management program does not appear to be common. Although other universities include a concrete lab, most of these universities incorporate this experience into a civil engineering curriculum, a technical certification degree program, or a degreed concrete management program, as opposed to construction management program. These universities include Purdue, California State University Los Angeles, Santa Clara University, University of Maine and Arizona State University. There are also universities which offer a degreed program in Concrete Industry Management (CIM) and these include Arizona State University, California State University Chico, Middle Tennessee University, New Jersey Institute of Technology, and Texas State University (www.concretedegree.com).

Course Background, History, and Topics

The concrete construction and asphalt pavement courses have both been offered at CWU for over 20 years in a consistent format, although changes are always being made to reflect advances in the construction industry, such as new concrete chemical admixtures and placing and finishing equipment. During this 20-year period laboratory exercises have been developed and refined, utilizing the acquisition of new lab equipment and a new lab facility. Topics incorporated into the course include concrete fundamentals, sustainability, desirable properties of fresh and hardened concrete, concrete aggregates, concrete mix water, air entrainment, admixtures, batching, mixing and transporting concrete, mix design, slabs-on-grade, placing, finishing and curing, hot and cold weather concrete placement, concrete formwork, and structural considerations in concrete.

The course incorporates a variety of delivery methods, including lectures, guest speakers, field trips and several laboratory exercises. The course typically averages about 24 students and the lab component of the course is divided into two separate sections with about 12 students in each section. Laboratory exercises assigned to students throughout the course include concrete aggregate and sand moisture content testing, concrete sand gradation analysis (ASTM C33), the slump test (ASTM C143) and making, curing, capping and testing 6 inch by 12 inch concrete cylinders (ASTM C31, C192, C511, C617, C39) (Kosmata & Wilson, 2011).

At Central Washington University the course is used to collect American Council for Construction Education (ACCE) Student Learning Objective (SLO) data for SLO #1 Create written communication appropriate to the construction discipline. The written communication created from these courses include written lab reports where students are required to calculate and describe water mix ratios, testing procedures, and report on the results of the testing procedures performed in the lab.

Methodology

A case study methodology approach was used to expand on the pedagogical content that can be utilized to create a concrete lab which will expand the construction management student knowledge in how concrete is tested and analyzed in either a lab or construction field situation. Therefore, the primary purpose of having the students make, cure, cap and test concrete cylinders is to familiarize them with proper ASTM procedures and provide a practical hands-on learning exercise where they can experience first-hand how varying the water-to-cement ratio for a concrete mix affects the compressive strength of the cured concrete. This information is covered in the text and in lecture, however the lab exercises give the students a better understanding and appreciation of engineering testing and also how technical specifications for concrete, as stated in a construction contract, relate to concrete on the job site. For example, specifications may call for a 14-day compressive strength for concrete in a building column of 3,000 pounds per square inch (psi). After going through the lab exercises the students can better visualize what is involved in making and testing concrete cylinders and what the fracture patterns on a 3,000 psi, 14-day cylinder break will actually look like. They also gain an understanding of the importance of proper concrete testing and how it relates to managing a concrete construction project to avoid delays and rework.

Facilities

The lab space is comprised of a 1,440 square-foot room on the first floor of a new technology building that houses the construction management program. The room is well lighted and has a concrete floor slab, work tables with stainless steel tops, casework and shelves for storage and a large integrated exhaust hood that vents to the building's roof. There are two stainless steel sinks in the room. One is a standard 30 inch double basin kitchen sink and the other is a larger four foot double basin industrial sink. Just outside the lab space is a large exterior concrete apron work area, complete with a grated washout pit and hose bib for cleaning tools and equipment used in the lab exercises. Water from cleaning is filtered by a drain system allowing cement and sand to settle in pit and manually cleaned and disposed of in a concrete recycling bin. Six 30-gallon galvanized steel garbage cans on wheeled dollies serve as storage containers for type I-II Portland cement, coarse aggregate and fine aggregate (sand). The aggregates are donated by a local batch plant and the instructor conducts the proper tests before the quarter begins to determine the absorption of the aggregates. This absorption value is provided to the students.

Equipment

Successful delivery of the labs is dependent on some basic tools and pieces of equipment, most of which are relatively inexpensive. Table 1 below shows a list of lab components and approximate cost. Much of the funding for the equipment was secured through donations from construction companies and private engineering and material testing firms.

Table 1

Concrete lab components and cost

Component	**Approximate Cost**
Plastic Mixing Tubs and Hand Tools	$300
Curing Tank (w/Thermometer and Spigot)	$500

Steel Garbage Cans w/Dollies (3 ea)	$650
Reusable Steel 6" x 12" Molds (6 ea)	$1,300
Capping Pots (2 ea)	$1,200
Compression Tester	$12,000
PPE: Rubber gloves, safety glasses, cleaning supplies	$300
Electronic Digital Laboratory Scales (3 ea)	$1,000

The concrete sand, aggregate and cement are stored in the steel garbage cans. For weighing and mixing the ingredients for the concrete cylinders students use electronic digital laboratory scales, small plastic buckets, a large plastic mixing tub, a mason's trowel and an ordinary garden hoe. Reusable 6" x 12" steel concrete cylinder molds are provided. The concrete curing tank shown in Figure 1 was made in-house and consists of a 24" x 36" x 24" deep galvanized steel livestock water tank mounted on an elevated stand with a water spigot for drainage. The tank is heated by a simple 120 volt 1200 watt magnetic automotive oil pan heater that attaches to the bottom of the tank and is controlled by a digital wall-mounted thermostat unit. This unit senses the water temperature through a thermocouple probe mounted to the tank rim. The thermostat has a variable set point and is set to maintain the temperature of the water in the curing tank at the ASTM specified 73º +/- 3º Fahrenheit.

Figure 1. Concrete cylinder curing tank

Cylinders are capped using a sulfur-based concrete cylinder capping compound that is heated in one of two 110 volts thermostatically controlled, electrically heated pots as shown in Figure 2 below.

Figure 2. Capping compound pot

The heated capping compound is used in conjunction with a capping mold to ensure the caps are smooth and perpendicular to the longitudinal axis of each cylinder. Figure 3 shows the capping mold utilized in the lab.

Figure 3. Capping mold

The concrete cylinders are tested with a large hydraulically operated concrete compression tester with a 250,000 pound capacity, measured in 500 pound increments. The tester shown in Figure 4 has an analog readout with a manual follower needle to record the break point and a safety cage to surround the cylinder (cage is not shown in the photo).

Figure 4. Digital Concrete compression tester with readout

Lab Exercises

The lab component of this course occurs five times throughout the quarter and each lab correlates with the topic covered in lecture at the time. The first two lab sessions are dedicated to gaining an understanding of the moisture content for both fine and coarse aggregate and conducting a sieve analysis on concrete sand. In the next three lab sessions the students are assigned to one of four groups with three students in each group. A standard mix design is assigned to the four groups and is identical except for the water-to-cement ratio, which varies by group. This mix design, as shown in Table 2, is then used both for the slump test exercise and for making concrete cylinders.

Table 2

Concrete mix design

Ingredient	Weight	Absorption
Fine aggregate (sand)	12 pounds	1.5%
Coarse aggregate	22 pounds	1.8%
Type I-II Portland cement	6.5 pounds	
Water	Varies by group	

The four groups' water-to-cement ratios (w/c) are 0.45, 0.50, 0.55 and 0.60. The absorption of the aggregates is given to the student groups so that they can make proper aggregate moisture adjustments to their mix design to account for the fact that the aggregates are not in a "neutral" moisture content condition, known as saturated surface dry. By varying the water-to-cement ratio students gain an understanding of how the water-to-cement ratio affects not only slump but also, after testing the cured cylinders, how it affects the compressive strength. This relationship between strength and the water-to-cement ratio is emphasized in the lecture but the lab exercise significantly reinforces this point.

Lab Procedures for Making, Capping, Curing and Testing Concrete Cylinders

In about the eighth week of the quarter the student groups meet in the lab and weigh the ingredients based on their assigned water-to-cement ratio, adjusting the aggregate weights to account for absorption and the current moisture content in the aggregates. Prior to starting the lab, students are briefed on the safety procedures necessary for conducting the lab. On the outdoor apron they then mix the dry ingredients in a plastic tub with a garden hoe and then add the proper amount of water to create their assigned water-to-cement ratio. The ingredients are again mixed and each group casts one 6 inch diameter by 12 inch high cylinder in a reusable steel mold, sprayed with a release agent, per ASTM procedures. The cylinders are then stored in the lab until the following day when one member of the group is responsible for stripping, marking and placing the group's cylinder in the curing tank. Since the lab is split and there are four groups in each lab there are eight concrete cylinders, representing four water-to-cement ratios, in the curing tank at the end of the second day.

Two weeks (14 days, +/-) after the cylinders are cast the entire class meets as a group and the instructor demonstrates the proper procedure, including the use of personal protective equipment (PPE) for capping the cylinders using the heated sulfur capping compound. Because the heated capping compound smells strongly of sulfur, the two heating pots are turned on early in the day and placed beneath the vent hood in the lab. In prior years, before the new facility was available, the pots were placed outdoors using extension cords. After demonstrating the capping procedure with one cylinder the instructor supervises the students as they cap the remaining seven cylinders. As they are being capped (the compound hardens in minutes) the instructor places the capped cylinders inside the safety cage in the hydraulic compression tester. Each cylinder is slowly loaded until failure. Typically in a testing lab the cylinders are tested until the load needle on the machine just begins to fall from its peak. This avoids total destruction of the concrete and eliminates messy cleanup. However, in this lab, for learning purposes, the cylinders are loaded until they fail completely. At a high water-to-cement ratio the cylinders merely crumble. However, at the lower water-to-cement ratios, 0.40 and 0.45, the cylinders can "pop" with a very loud explosion. This in itself is a very effective tool to demonstrate to students the dramatic effect of varying the water-to-cement ratio.

Another benefit of breaking the cylinders completely is that the students can observe first-hand how the water-to-cement ratio affects the mode of failure. It is obvious that failure of the weaker mixes is the result of failure of the cement paste; it pulls away from the aggregate while the stronger mixes show marked aggregate fracture. In this case the cement paste has bound to the aggregate and is actually stronger than the aggregate itself. The load at failure, in pounds, for the eight cylinders is then recorded. The compressive strength is calculated using a spreadsheet and the corresponding results are graphed and presented to the students at the next class meeting.

Results

Students indicate that it is very beneficial to have the opportunity to see in person how concrete with a low water-to-cement ratio can become stronger than the aggregate itself after only 14 days of cure time, as demonstrated by the aggregate fracture shown in Figure 5.

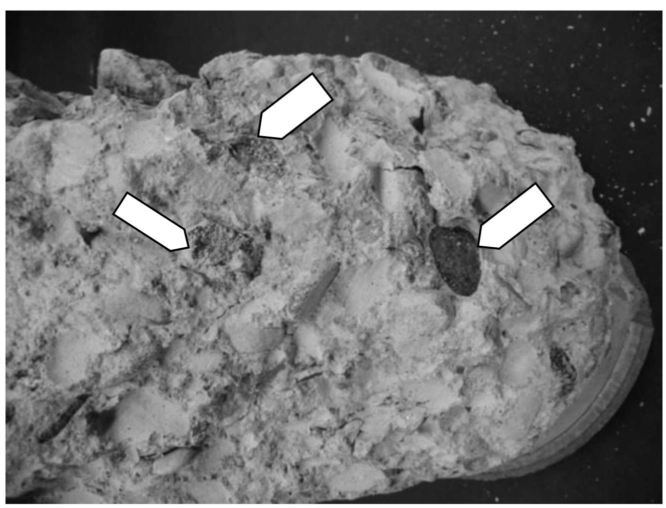

Figure 5. Aggregate fracture in cylinder with low water-to-cement ratio mix

Numerical results for the past year are shown in Table 3 and Figure 6. Note that the results from each of the two groups representing a specified water-to-cement ratio have been averaged before they are tallied. These results are presented to the students and clearly indicate that an increase in water-to-cement ratio decreases compressive strength. The results are also beneficial to the students because they are reasonably consistent with what is presented in the text and lecture. The class uses these results as a learning tool by discussing how water is often added to concrete in a mix truck on a job site to make the concrete more workable and easier to place, without thorough knowledge of the long-term effect this will have on hardened concrete.

Table 3

Concrete cylinder data

W/C Ratio	**Area (in^2)**	**Group 1 Load (lbs)**	**Group 2 Load (lbs)**	**Avg (lbs)**	**psi**
0.45	28.27	133,000	152,500	142 ,750	5050
0.50	28.27	130,000	124,000	127,000	4492
0.55	28.27	85,000	102,000	93,500	3307
0.60	28.27	61,000	84,000	72,500	2565

Curing time: $14^{+}/_{-}$ days

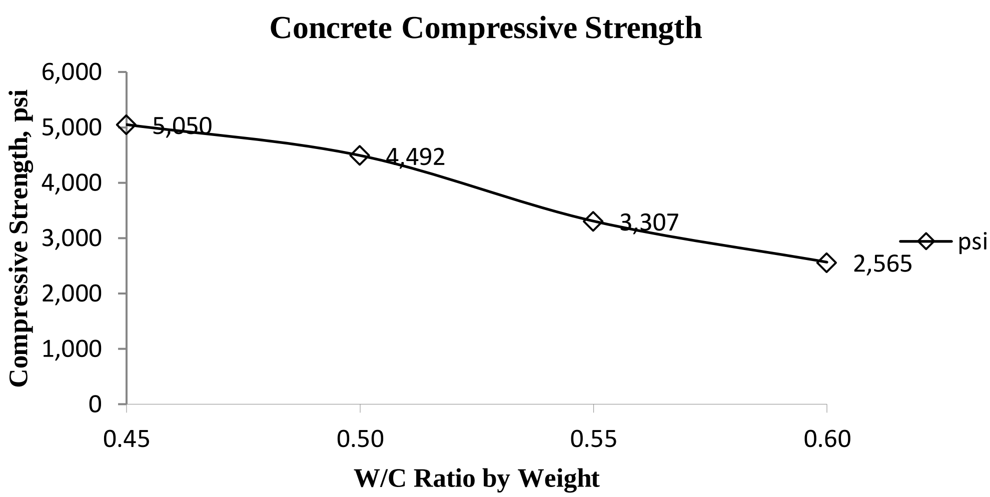

Figure 6. Compressive strength graph by water cement ratio

Discussion and Conclusion

Based on the results of this study, incorporating ASTM-based lab testing exercises into a concrete and asphalt materials class in a construction management program has proven to be a positive experience. Anecdotal evidence has demonstrated that the students thoroughly enjoy the chance to actually batch, mix, and place a concrete mix in test cylinders. They learn what a concrete mix will look like if the water-to-cement ratio is increased, about compression failures, and how compressive strength is affected by an increase in the water content of a mix. Additionally, when students are exposed in the lab to the different concrete mixtures, they can gain a "visual" or hands-on perspective as to the consistency of the concrete, which is a good reference for field applications as fresh concrete is placed in the field from the truck to final placement. Then referring to individual student calculations and the actual concrete mix in the lab brings the theory and hands-on application together.

Establishing the lab has been an ongoing process and a learning experience. Most of the equipment is relatively inexpensive, readily available at a local hardware store or from a testing/engineering supply company and easy to store and use. The one exception is the heavy and bulky hydraulic concrete compression tester, which carries a price tag of approximately $12,000. One possible way to create a lab experience for students without this cost would be to have the students make the cylinders in the lab and then use a field trip to a local testing lab to have these cylinders tested. Future hands-on laboratory learning opportunities for students include reinforced concrete beam and concrete mix design contests. These laboratory experiences will further expose students to the technical properties of concrete, the use of concrete as a building material and the managing of concrete on construction projects.

In conclusion, the real contribution of this study to the "construction management" body of knowledge shows there is little information on how educators can develop a concrete lab creating a hands-on environment for students to understand the engineering properties necessary for the proper testing and management of concrete construction in field operations. This case study identifies the types of equipment, costs, and basic lab approach that can be implemented at any construction management program. Additionally, this case study expands from the theory most civil engineering programs might offer to a virtual experience where students can see and experience the results when working with water to cement ratios. There are studies that do show how problem-based learning in a concrete lab can be facilitated, but these studies do not discuss the types of equipment or get into the specifics on how concrete cylinders can be utilized in a lab scenario following the ASTM standards. Therefore, this case study provides the necessary gap in the construction management education for any instructor to develop a hands-on lab for in concrete which is especially important for those newer professors who are looking for ideas on concrete construction lab content.

References

Arumala, J.O. (2002). Student-Centered Activities To Enhance The Study Of Structures. *ASC Proceedings of the 38th Annual Conference. Virginia Polytechnic Institute and State University, Blacksburg, VA*, 1-16.

Concrete Industry Management (2012). http://www.concretedegree.com/index.html

Gier, D.M. and Hurd, M.W. (2004). Increasing the Effectiveness of Active Learning Exercises in the Construction Management Classroom. *ASC Proceedings of the 40th Annual Conference, Brigham Young University, Provo, UT*, *http://ascpro0.ascweb.org/archives/cd/2004/2004pro/2003/Gier04.htm*
.

Kosmata, S.H. and Wilson, M.C (2011). Design and Control of Concrete Mixtures: The guide to applications, methods, and materials (15th Ed.). Farmington Hills, MI: Portland Cement Association, 421-426.

Stein, J. and Gotts, V. (2001). Analysis of Selected Learning Preferences of Construction Management Students. *ASC Proceedings of the 37th Annual Conference, University of Denver, Denver, CO*, 41-48.

Ageism: A Threat to Career Progression Despite Labor Shortage in the Construction Industry

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Considering the degree and rate of aging of construction workers around the globe, which is compounded by intensifying labor shortages, the industry requires serious attention to workplace policies that safeguard older workers against ageist stereotypes and prevent early retirement while at the same time attracting younger workers. Ageism has been identified as a barrier in all four layers of career progression (recruitment and hiring, retention, promotion, and firing/dismissal). Therefore, the steps to tackle ageism in the construction industry need to include a strategy that ensures the career progression of older and experienced workers, and an approach that welcomes a more diverse young workforce. Through a comprehensive literature review, this research sought to explore the current state of ageism in the construction industry. The findings of this research show that even though minimal research has been conducted thus far, there is a strong business case that justifies further research in this area. Research findings further point out to ageism as a threat in career progression. Sources of ageism barriers include societal and employer attitudes, coded language, and worker self-directed ageism. This research recommends both quantitative and qualitative analyzes of the prevalence and impacts of ageism in the construction industry.

Key Words: ageism, construction industry, older workers, career progression

Introduction

Given the forgoing construction labor market conditions facing a shortage of labor and skills, there is a need to retain experienced and high-performing older workers longer. This assertion is confirmed by previous research that suggest that performance of older workers is better in comparison to those who are younger because of their experience (E.g., North, 2019; Loretto & White, 2006). However, one major obstacle facing recruitment/hiring, promotion, and retention of aging workers is ageism which is characterized by discriminatory stereotypes, behaviors, and attitudes toward older workers. Such practices have the potential of discouraging and demoralizing aging workers from seeking and remaining in the workforce. In the process, valuable experience is lost while at the same time the problem of labor shortage is escalated.

The construction industry median age is 43 years old with majority of the workers lying between ages 45-64 (O'Connor, 2021; Seniorliving.org, 2020) in comparison to the United States (U.S.) workforce average age that is forecasted to rise from 42.0 to 42.3 years between 2016 and 2026 (FOR CONSTRUCTION PROS.com, 2019). It is also forecasted that the proportion of workers in the U.S. aged over 55 years in 2024 will be double the figure in 1994, increasing from 11.9% to 24.8% (FOR CONSTRUCTION PROS.com, 2019). Therefore, the degree and rate of aging of construction workers in the United States compounded by intensifying labor shortages, the industry requires serious attention to policies that safeguard older workers against ageist stereotypes and prevent early retirement. Furthermore, even if replacements for older workers were to be found, there are fears that valuable experience will be lost as older workers retire.

In the U.S., statistics from Equal Employment Opportunity Commission (EEOC) show that age discrimination-related cases have been on the rise. In monetary terms, research by Kolmer (2021), argued that the US economy lost $850 billion in 2018 due to ageism. Further, Kolmer (2021) argued that more than $91 million had been recovered from employers in ageism-related lawsuits from 1967 to 2021. For individual cases, the most expensive cases have cost companies between $2.85 million and $250 million (Kolmer, 2021). This is clear evidence that ageism is a significant problem in the workplace. These statistics point out that ageism could be a threat to one's career progression if these trends were to remain persistent.

Despite the Federal and state laws to protect individuals against age discrimination in the workplace, the vice is still prevalent. According to Kolmer (2021), 67% of workers aged 40-65 will continue working beyond age 66, which means that the number of older workers likely to stay in employment will increase. This increasing number will be exposed to ageist attitudes and stereotypes as research reveals that at least 60% of older employees have experienced or seen ageism with 90-95% of those saying that ageism at the workplace is common (Kolmer, 2021). Additionally, at the recruitment and hiring phase, older workers are 40% less likely to be offered jobs in comparison to workers who are younger. This same trend is noted with promotion and firing of older employees.

Therefore, this paper aims at examining how ageism could be related to an individual's career progression in the wake of labor shortage in the construction industry. Through a literature review and existing data from government agencies, the paper will focus on how ageism could be a threat to the major milestones in one's career otherwise referred to as layers of career progression in this paper. Talent acquisition, hiring managers, human resource departments, supervisors, and construction management professionals, in general, will find this paper useful in understanding the scale and breadth of ageism in relation to a career progression in construction which ultimately can be a solution to the much-needed staffing demands of the industry. This paper will also advance knowledge through the introduction of this novel idea which has been well-advanced in other sectors into construction practice and research.

Ageism defined

The definition of ageism has evolved throughout these years. The word ageism was first explained by Robert Butler who explained ageism as a preconceived notion of one age group against another (Butler, 1969). This definition addressed the prejudicial notion due to the generational gap and further noted the same to be a national problem. Butler contended that ageism is a form of prejudice where younger and older age groups are discriminated upon by the middle-aged group who society assumes responsibility for the well-being of the younger and older age groups. For further understanding of ageism, he juxtaposed the effects of negative stereotypes of ageism to those of racism and social class as well as the intersections with other forms of prejudice (Butler, 1969). In his ensuing research, Butler (1980) carried on with comparisons between ageism, racism, and sexism, where he argued that ageism manifests itself as attitudes, behaviors, and institutionalized policies and practices against older individuals.

A broader definition of ageism corresponds ageism to age-based discrimination. Age-related stereotypes are ignored most of the time and people fail to notice their consequences because they are ingrained in society. This definition of ageism has further been explained broadly as discrimination against or in favor of one age group against the other. While ageism affects the young and the old most, because these two groups are mostly assumed to dependent (Angus & Reeve, 2006), people in the mid-age group may also be affected (Lloyd-Sherlock et al., 2002). Further definitions of ageism include behavioral, cognitive, and emotional aspects; implicit and explicit nature; positive and negative consequences; and how it is manifested (Ayalon & Tesch-Römer, 2018).

Similarly, different people of different age groups respond differently to similar ageist acts because of varying life experiences, backgrounds, and histories. Everyone, at different levels, is involved in the formation of attitudes and behaviors toward ageism through interaction, negotiation, and ongoing discursive processes. Existing research reinforces this by arguing that as people age, they exhibit and maintain certain attitudes which may or may not be ageist, while at the same time they are likely to engage in self-directed ageism (e.g., Rocha et al., 2022; Krekula et al., 2018). Thus, if age were not to be used as an organizing principle at the workplace, it would form a compelling case since such a situation would be perceived as being neutral and would give an institution or firm an object through which recruitment, and hiring, retention, promotion, and dismissal occurs.

Ageism in the construction industry

The imminent retirement of baby boomers and decreasing fertility rates in the United States since 1960 which has shrunk groups of younger prospective employees who could potentially rise the ranks and replace the aging workers has led to labor shortages in the country. The same scenario is replicated in many countries in Europe and Australia (World Health Organization, 2021). Globally, 2020 statistics show that the percentage of workers in the construction industry aged 55 and over, were almost twice the number in 2003, rising from 11.5 percent to 22.7 percent. This increase can also be attributed to the aging of the entire population. However, in comparison to the employed population, the proportion of aged workers is more pronounced for the construction industry.

Additionally, urgent attention is needed in the recruitment and retention of older workers in the industry. Disseminating currently available ageism laws and guidelines in the US and other countries around the world may require changes in work organizations and improved workplace standards and enforcement. Moreover, the steps to tackle the current skills shortage in the construction industry need to include an approach to ensure the retention, training, and promotion of older and experienced workers, and an approach that welcomes a more diverse workforce. This approach could respond to existing laws and policies on ageism that focus on individuals older than 50 years ignoring steps taken by organizations to recognize a younger workforce. On this basis, there is a lack of research focusing on ageism and younger workers which in its entirety ignores the true definition of ageism - a phenomenon directed toward all age groups.

Theoretical framework

Ageism has been described as a social issue through biases by one age group against another. Population demographics are changing in all sectors of the economy and both current and projected data show that the average age of construction industry workers is above the overall average age of the current workforce (Sokas et al., 2019). This, therefore, mean that the demographics of the construction industry workers from an age perspective is changing and an understanding of what this means from a societal standpoint is timely. One such societal issue is ageism. To understand ageism in the construction industry, a theoretical framework in figure 1 is proposed and used as guide in this paper.

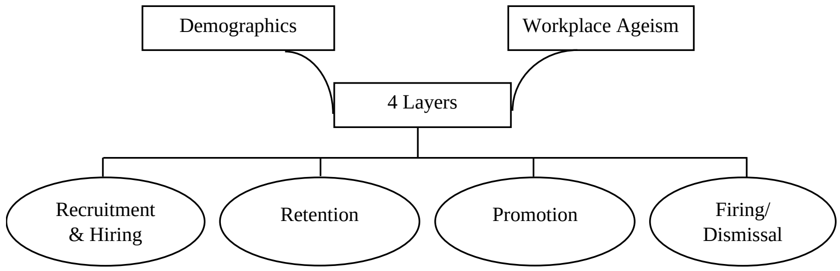

Figure 1. Theoretical framework for ageism in the construction industry.

The theoretical framework proposed and presented in figure 1 is used as a point of departure in this paper to guide the investigation of the existence and state of ageism research in the construction industry. The framework provides four layers to an individual's career progression in changing demographics in the construction industry. The four layers include 1) recruitment and hiring, 2) retention, 3) promotion, and 4) firing/dismissal. The theoretical framework specifically brings together the four most important milestones in one's career (i.e., how one finds a job, tenure, and career progression through promotion). However, ageism can be a barrier to achieving any or all these four layers of an individual's career. For example, research has shown that access to specialized training and education in the workplace decline significantly with age (World Health Organization, 2021), research in the United Kingdom (UK) showed that 26 percent of workers aged 39 to 54 reported age as a barrier to career progression with two-thirds contending that ageism barrier was difficult to overcome (Baska, 2020). Ageism issue in the UK gets even worse as one gets older according to research. According to Frith (2017), 46 percent of those over 55 cited ageism as their biggest barrier to career progression compared to 27 percent of those aged between 34 to 54.

Methods

The literature review methodology as used in this research renders a qualitative approach for the authors to comprehensively agglomerate findings from articles reviewed to draw common themes and differences and use such findings to reach a conclusion. An in-depth search was carried out in ProQuest and Google Scholar databases using keywords. The Keywords of "ageism in construction industry", "ageism law", and "age discrimination in the construction industry" were used to conduct the search. Also, Google search engine was used to find current laws and policies that exist in the US to protect workers against ageism. To narrow down the focus of this research, keywords were limited to either the abstract or the title. Since this is an emerging social issue, it was expected that research study on ageism in the construction industry is limited and therefore, the search was not focused on a given construction type, but rather on the entire construction industry organization. Furthermore, the search was also expanded to cover other relevant literature from other industries. A review for relevance of the articles found from the search engines resulted in 65 studies that were considered for an in-depth analysis. The in-depth analysis established that 32 publications contained relevant information for the current research. Thematic analysis was utilized to help identify, analyze, and interpret patterns in the publications containing relevant information.

Findings

The findings presented in this paper are summaries of the existing body of knowledge derived from the analyzed articles. These findings are organized based on the theoretical framework (figure 1) that was used as a guide for this research study.

Current state of practice

This paper searched papers on ageism from major data databases and in particular, Google Scholar and ProQuest. It is noted that construction-specific research in this area is limited. Therefore, the paper borrows relevant materials from other industries to draw conclusions that can be applied in the construction industry. The other industries that published articles covered include gerontology, family science studies, human resource and talent acquisition, and nursing. The current trends relating to ageism and the four layers of career progression were researched and top literature findings with each layer presented as a subtopic.

Recruitment and hiring

The findings show that older workers were less likely to be invited for a job interview or considered for a job offer compared to younger applicants (e.g., Batinovic et al., 2022; Neumark, 2021). Furthermore, countries that have laws protecting older workers such as the US, show that there is less discrimination when the law requires larger damages to employers exercising such discrimination. For example, research by Neumark et al., (2019) shows evidence that there is less discrimination in US states where violators of discrimination laws are required to pay larger damages.

Research has shown that recruitment and hiring professionals are significantly less likely to rate job applicants aged over 45's as being job ready, being the best fit for the company culture, or having the best experience compared to candidates 35-44 years (McLaren, 2021). Further, this research shows that even the younger applicants aged 18-34 years were rated higher than those over 45 in all these categories. Another study showed that those over 50 years were up to three times more likely to be called for a job interview compared to a candidate 28 years old (Epstein, 2022). These statistics show a perception bias by the recruitment and hiring managers about older candidates. Similar studies show that when older people are given a chance, 87% of them perform better than their younger counterparts (McLaren, 2021). What this means, therefore, is that there is a difference between perception and reality. The task here is convincing and changing the perception of recruitment and hiring managers. What this does to older workers is that it leads to self-directed ageism (North, 2019), and they end up making concessions. For example, statistics reveal that in some way, 66% of older workers lowered their expectations, 30% ended up taking jobs in an area that they didn't want, 29% accepted lower salaries, and 24% accepted to step back and take lower positions (McLaren, 2021).

It is not only older candidates who receive rejections; younger jobseekers can also be denied job opportunities because of their age. However, this area of research on ageism is less studied and has received less attention partly because most laws and policies in place tend to focus on older workers. Studies that exist reveal that younger employees lack experience, are unmotivated and have other related stereotypes and thus they cannot be hired (Epstein, 2022).

Retention

Recruitment studies based on experimental research were used in this paper to draw a line of argument on this layer of career progression. For example, a study by North (2019) shows that older workers were denied training opportunities as compared to equally qualified younger counterparts. Training opportunities can be a motivating factor for workers to remain on the job. This argument then implies that retention on the job can be either voluntary o forced turnover. Harris et al. (2018) reviewed past research on ageism and older workers and found varied results in terms of retention. Studies in Spain, Greece, the Netherlands, and United Kingdom showed that employers had intentions for older worker retention at varying degrees, while on the other hand studies in China showed decreased intention for older worker retention and forced retirement (Harris et al., 2018).

Ageism and ageist prejudice assume that a younger employee will be with the employer longer. This assumption is not likely nowadays as research has shown that on average, young employees leave their jobs after three years in contrast with older employees who on average, provide employers with longer tenures and more stability (Lipnic, 2018).

Promotion

Audit studies were used to gain insights into this third layer of career progression. A survey of older employees shows that 12% of older workers reported being bypassed for a chance to take up a senior position due to their age (Perron, 2018). In the US, the Missouri Department of Transportation (MoDOT) has lost multiple lawsuits due to age discrimination. For example, *McClurg v. MoDOT* (Vockrodt, 2014) and *Justus v. MoDOT* (White, 2013) who were demoted from their positions due to their age. It is common practice in the workplace where it is suggested that someone consider retirement because of their age. Nevertheless, such positions are taken by younger workers.

Firing

The data that were used in informing this layer in an individual's career progression were obtained either from past research based on qualitative analyses or from publicly available data from the EEOC. Older employees are facing challenges with increasing rates of unwilling job losses. For example, research shows that 7% of the workers were laid off or forced to leave their positions because of their age (Perron, 2018). Furthermore, findings from that same research revealed that 18% of older workers fear losing their jobs due to their age (Perron, 2018).

Data mined from health and retirement studies as well as surveys with workers over 50 years show that more than 50 percent of U.S. older workers are forced to let go of their positions, laid off, or fired on their way to retirement (Gosselin, 2018). The prevalence of ageism in the US can be evidenced by the number of claims and cases filed with EEOC. Of such cases, there have been successful lawsuits for dismissal due to age. For example, *Reid v. Google, Inc., 2010* where reid successfully sued Google for termination due to his age. Other examples include recruitment and construction companies in Australia who were penalized due to age discrimination (Surpportah, 2021).

Sources of ageism barriers

An analysis of published literature, the sources of ageism barriers can be categorized broadly into societal and employer attitudes, coded language, and worker self-directed ageism. Societal and employer attitudes include stereotypes against older workers. These stereotypes, for example, act as a constant reminder that as one age, they are only destined to die (Martens et al., 2004), older workers are a burden to their employers since they are more costly (Kroon et al., 2018), older workers are systematically ignored by society (Thompson & Arrighi, 2007). These societal and employer attitudes are hurdles to career progression among older people.

Coded language as used mostly in recruitment and hiring is a source of barriers. Coded language can also be seen in the other layers of career progression. It is common to see job postings including languages such as "…fit in with a young team" (McGoldrick & Arrowsmith, 1993), "new or recent college graduate" (Kopytoff, 2014), "cultural fit" (McGann, et al., 2016). When such coded language is used in the workplace, it denies older workers an opportunity either to get hired, earn a promotion, or even they can be involuntarily dismissed.

As workers age in an ageist society and are exposed to ageism stereotypes, it can lead to self-directed ageism. For example, job responsibilities that require memory tasks will undermine performance. Feeling old or young is very subjective and thus this source of ageism barrier can be broad in its analysis and deep in understanding (Angus & Reeve, 2006).

Conclusion

Ageism is still a problem around the globe costing global economies billions of monies. The aim of this paper, therefore, was to explore ageism as a barrier to career progression in the face of labor shortages in the construction industry. Based on the current trends in the labor market which means that there are lower unemployment rates and growing skilled labor shortages, hiring, and retaining older workers can help construction firms fill open positions. To achieve this, recruiters and hiring managers should attract workers of all ages and avoid basing their hiring decisions on age and years of experience limitations despite their qualifications.

The prevalence of ageism is real, and it is on the rise globally. Therefore, ageism can be a threat to an individual's career progression at any of the four career progression layers presented in this paper. Therefore, strategies that can offer career guidance and counseling to workers of all ages at all career progression layers are recommended. Retention of workers by an organization will reduce costs related to employee turnover, retain knowledge, and experience and ultimately improve productivity. Sources of ageism barriers were also reviewed in the paper. There is sufficient evidence to show that societal and employer attitudes, coded language, and worker self-directed ageism can be obstacles to an individual's career progression.

The effects of ageism in an industry that is facing labor shortages and skills is the loss of valuable experience due to forced retirement or early retirement for those facing ageism. In terms of hiring, the reluctance of construction firms to hiring older workers means that these firms will continue finding it difficult to fill open positions. Research has shown that older workers tend to perform better due to their experience which is a strong message to construction companies not to shy away from hiring this group of workers.

The paper extends the body of knowledge by exploring this emerging social issue in construction research and concludes that ageism is a threat to an individual's career progression. Ageism is practiced at the recruitment/hiring level, retention, promotion, or firing/dismissal level. These layers are all essential is career progression and once ageist prejudices take control of the processes and process in a company, then an individual's career can stagnate or even come to an abrupt. Ageism in the construction industry is in its early stages. This paper, therefore, recommends an in-depth analysis of ageism both to the older and younger workers. Exploration of industry wide practices is also recommended through the analysis of job advertisements, promotion, and tenure policies as well as dismissal. Additionally, this research recommends both quantitative and qualitative analyzes of the prevalence and impacts of ageism in the construction industry.

References

Angus, J., & Reeve, P. (2006). Ageism: A threat to "aging well" in the 21st century. *Journal of applied gerontology*, 25(2), 137-152.

Ayalon, L., & Tesch-Römer, C. (2018). *Contemporary perspectives on ageism.* Berlin, Germany: Springer Nature.

Baska, M. (2020, February 13). *Age biggest barrier to career progression, survey finds*. Retrieved from People Management: https://www.peoplemanagement.co.uk/article/1742752/age-biggest-barrier-career-progression-survey-finds

Batinovic, L., Howe, M., Sinclair, S., & Carlsson, R. (2022). Ageism in hiring: A systematic review and meta-analysis of age discrimination.

Butler, R. N. (1969). Age-ism: Another form of bigotry. *The gerontologist*, 9(4_Part_1), 243-246.

Epstein, S. (2022, January 18). *Age-related biases are baked into the recruiting process, whether conscious or not. Should workers be cagey, in order to overcome recruiters' biases?* Retrieved from BBC: https://www.bbc.com/worklife/article/20220118-cv-ageism-can-you-be-the-wrong-age-for-a-job

FOR CONSTRUCTION PROS.com. (2019, June 4). Retrieved from Median Age of US Construction Workforce Increases to 42: https://www.forconstructionpros.com/business/press-release/21071485/national-association-of-home-builders-median-age-of-us-construction-workforce-increases-to-42#:~:text=National%20Association%20of%20Home%20Builders%20(NAHB)%20analysis%20of%20the%20most,A

Frith, B. (2017, March 15). *Age is biggest barrier to career progression*. Retrieved from HR Magazine: https://www.hrmagazine.co.uk/content/news/age-is-biggest-barrier-to-career-progression

Gosselin, P. (2018, December 28). *How We Measured Involuntary Job Losses Among Older Workers*. Retrieved from ProPublica: https://www.propublica.org/article/how-we-measured-involuntary-job-losses-among-older-workers

Harris, K., Krygsman, S., Waschenko, J., & Laliberte, R. D. (2018). Ageism and the older worker: A scoping review. . *The Gerontologist*, 58(2), e1-e14.

Kolmer, C. (2021, August 31). *Zippia - The career expert*. Retrieved from Age discrimination statistics [2022]: https://www.zippia.com/advice/age-discrimination-statistics/

Kopytoff, V. (2014, June 19). ech industry job ads: Older workers need not apply. . *Fortune*.

Krekula, C., Nikander, P., & Wilińska, M. (2018). Multiple marginalizations based on age: Gendered ageism and beyond. In *Contemporary perspectives on ageism* (pp. 33-50). Springer, Cham.

Kroon, A. C., Van Selm, M., Ter Hoeven, C. L., & Vliegenthart, R. (2018). Reliable and unproductive? Stereotypes of older employees in corporate and news media. . *Ageing & Society*, 38(1), 166-191.

Lahey, J. N. (2008). Age, women, and hiring an experimental study. . *Journal of Human resources*, 43(1), 30-56.

Lipnic, V. (2018, June). *The State of Age Discrimination and Older Workers in the U.S. 50 Years After the Age Discrimination in Employment Act (ADEA)*. Retrieved from U.S. Equal Employment Opportunity Commission: https://www.eeoc.gov/reports/state-age-discrimination-and-older-workers-us-50-years-after-age-discrimination-employment

Lloyd-Sherlock, P., Guntupalli, A., & Sempé, L. (2002). Age discrimination, the right to life, and COVID-19 vaccination in countries with limited resources. *Journal of Social Issues.*

Loretto, W., & White, P. (2006). Employers' attitudes, practices and policies towards older workers. . *Human resource management journal*, 16(3), 313-330.

Martens, A., Greenberg, J., Schimel, J., & Landau, M. J. (2004). Ageism and death: Effects of mortality salience and perceived similarity to elders on reactions to elderly people. . *Personality and social psychology bulletin*, 30(12), 1524-1536.

McGann, M., Ong, R., Bowman, D., Duncan, A., Kimberley, H., & Biggs, S. (2016). Gendered ageism in Australia: Changing perceptions of age discrimination among older men and women. Economic Papers . *Journal of applied economics and policy*, 35(4), 375-388.

McGoldrick, A. E., & Arrowsmith, J. (1993). Recruitment advertising: Discrimination on the basis of age. . *Employee relations.*

McLaren, S. (2021, August 23). *Even in a Candidate's Market, Ageism Exists in the Hiring Process*. Retrieved from LinkedIn : https://www.linkedin.com/business/talent/blog/talent-acquisition/ageism-in-hiring-process

Neumark, D. (2021). Age discrimination in hiring: Evidence from age-blind vs. non-age-blind hiring procedures. . *Journal of Human Resources*, , 0420-10831R1.

Neumark, D., Burn, I., Button, P., & Chehras, N. (2019). Do state laws protecting older workers from discrimination reduce age discrimination in hiring? Evidence from a field experiment. . *The Journal of Law and Economics*, 62(2), 373-402.

North, M. S. (2019). A GATE to understanding "older" workers: Generation, age, tenure, experience. *Academy of Management Annals*, 13(2), 414-443.

Perron, R. (2018, July). *The Value of Experience: Age Discrimination Against Older Workers Persists*. Retrieved from AARP RESEARCH: https://www.aarp.org/research/topics/economics/info-2018/multicultural-work-jobs.html

Reid v. Google, Inc., S158965. (0 Cal. 4th 512, 113 Cal. Rptr. 3d 327 August 5, 2010).

Rocha, N. M., Maia, R. D., Marques, G. M., & Bandeira, R. L. (2022). Intersectionalities and Old Age: Ageism in the Crossroads of Race, Gender, and Age. In *Racism and Human Development* (pp. 163-172). Springer, Cham.

Sokas, R. K., Dong, X. S., & Cain, C. T. (2019). Building a sustainable construction workforce. . *International Journal of Environmental Research and Public Health*, 16(21), 4202.

Surpportah. (2021, October 18). *Construction and recruitment companies penalised for age discrimination*. Retrieved from Human Rights Claims: https://humanrightsclaims.com.au/construction-and-recruitment-penalised/

Thompson, E. H., & Arrighi, B. (2007). Older men as invisible men in contemporary society. Understanding inequality: *The intersection of race/ethnicity, class, and gender*, 289-298.

Vockrodt, S. (2014, November 12). *Former employees say Missouri Department of Transportation leaders preyed on older workers*. Retrieved from The Pitch: https://www.thepitchkc.com/former-employees-say-missouri-department-of-transportation-leaders-preyed-on-older-workers/

White, M. (2013, July 26). *MoDOT responds to lawsuit*. Retrieved from News-Press Now: https://www.newspressnow.com/news/local_news/modot-responds-to-lawsuit/article_49126b97-b774-58a2-a0d8-11ca7a7f176a.html

World Health Organization. (2021). *Global report on ageism.* World health organization.

Envisioning the Future of Supply Chain Management for Modular Construction through literature review

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Modular construction has been gaining momentum worldwide due to its potential in increasing project efficiency and reducing construction waste. It is centered around the utilization of prefabricated components and modules produced in off-site factories. Due to its unique features and close relationship with manufacturing industry, the supply chain management of modular construction requires more attention since transporting standardized modular parts with different completion levels is complicated to manage. What's more, the supply chain mapping and scheduling need to be improved due to the more specific requirements in terms of module components categories, building types, and labor availability and cost. In this research, the goal is to envision the future of modular construction supply chain management for more proactive adoption of modular construction. After conducting a systematic literature review, this research provides insights and recommendations for the current mapping design, scheduling, monitoring, and risk management. The contribution of this research involves the cost-benefit analysis of modular construction and a proposal for an enhanced supply chain system to increase logistics efficiency.

Key Words: Modular Construction, Supply Chain Management, Risk Management, Literature Review

Introduction

According to the definition of Construction Industry Institute (CII) (CII, 2011), modular construction (MC) includes all the work representing substantial offsite construction and assembly of components as well as finished projects onsite. It is based on the utilization of panelized components or full volumetric units which are produced in off-site factories and transported for assembly at the targeted areas (Ferdous, Bai, Ngo, Manalo, & Mendis, 2019), improving efficiency of the whole project delivery. Modular construction enhances productivity by dividing the complex onsite construction process into numerous stages within the off-site factories and assembly workhouses (Choi, Chen, & Kim, 2019; Council, 2009; Enshassi, Walbridge, West, & Haas, 2019).

Modular construction has been attracting numerous construction firms and practitioners for enhancing their project performance due to its advantages in budget and schedule predictability, assurance in quality as well as reduction in waste management and labor demand (Baldwin, Poon, Shen, Austin, & Wong, 2009; O'Connor, O'Brien, & Choi, 2014, 2016). What's more, based on the statistics from Markets (2020), the global construction is expected to become $12,031.1 billion with an annual growth rate of 5.7% by the end of 2024, in which modular construction is estimated as increasing at a 8.16% annual growth rate, demonstrating significance in market expansion within the construction industry. However, the potential of modularization of construction projects has not been fully capitalized due to their unique risks and uncertainties (O'Connor et al., 2014). One of the unique features for modular construction is that it's more sensitive to its supply chain since most of the prefabricated parts are constructed in the off-site factories or warehouses rather than assembled on site. Project modularization is "breaking up the whole process into discrete pieces", while supply chain management is considered as the network to integrate those "discrete pieces". Hence, this integration process requires the transportation of modules and module parts range from different completion levels, making it more complicated to manage. Besides, as type of modular construction differs, so does the required prefabrication components. Required building systems and materials varies among different types of buildings on the basis of building functions, special needs, and sustainable requirements. Therefore, supply chain mapping and scheduling should be improved due to the more specific requirements in terms of module components categories, building types, and labor situation including availability and cost.

In this research, the goal is to envision the future Modular Construction Supply Chain Management (MCSCM) for more proactive adoption of modular construction. Through literature review, this research provides insights and recommendations for the current mapping design, scheduling, monitoring, and risk management. The contribution of this research involves the cost-benefit analysis of modular construction and a proposal for an enhanced supply chain system to increase logistics efficiency.

Research Methodology

In order to understand how to improve the MCSCM, its features and process should be investigated and summarized first through a systematic literature review (see Figure 1). Furthermore, articles discussing about risk factors for determining the feasibility of modular construction in metropolitan areas should be studied as well. Last but not least, literatures focusing on classification of current modular construction supply chain should be analyzed to allocate resources more efficiently.

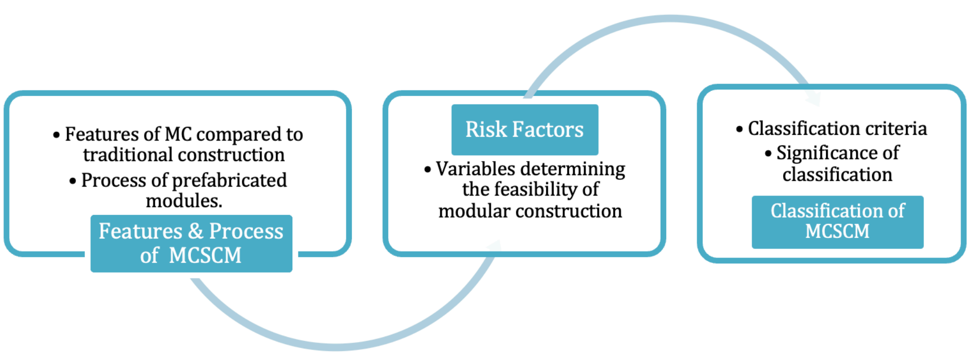

Figure 1 Literature review process and topics

Due to the academic influence of American Society of Civil Engineering (ASCE), numerous articles from journals of ASCE are under review. Here are the results of the article selection searching on Web of Science while the input keywords are “modular construction” and “supply chain” (see Table 1).

Table 1

Representative papers of the literature review

Source	Contribution	Research Methodology
(D. Lee & Lee, 2021)	Discuss about the implementation of digital twins to help predict potential logistics risks and accurate module delivery time.	Conducted a case study integrates BIM and GIS for real-time logistics simulation in modular construction to test the model performance.
(Doran & Giannakis, 2011)	Identify the application of supply chain practices of modular construction.	Conduct a case study to examine the construction supply chain from module manufacturer to module client.
(Hsu, Angeloudis, & Aurisicchio, 2018)	Provide insights about how to optimize logistics system of modular construction.	Conduct a case study adopting the stochastic supply chain network design.
(Hsu, Aurisicchio & Angeloudis, 2019)	Introduce a mathematical model for optimizing risk-averse logistics configurations for modular construction.	Conduct a case study demonstrating the performance of the model with multiple sources of uncertainty.
(Innella, Arashpour, & Bai, 2019)	Discuss the implementation of lean techniques in the modular building industry.	Conduct a comprehensive review of lean methodologies and tools connect lean with modular construction.
(Lee, Park, Lee & Hyun, 2019)	Propose a classification result of modular building construction projects based on schedule-driven.	Develop a simulation model and conduct a case study to test the reasonability of the classification.
(Liu & Lu, 2018)	Describes risk factors and impacts of the identified risk factors on project cost and duration for modular construction	Rank the risk factors with analytic hierarchy process (AHP).
(Ramaji & Memari, 2016)	Reviews the hierarchy of modular building components.	Review literature about interactions, functionality, and attributes of modular building’s product architecture model.
(Sun, Wang & Zhao, 2020)	Provide reference for stakeholders adopting modular buildings with how to mitigate risks.	Review literature about constraints of modular buildings, conduct a questionnaire survey to determine domain constraints.
(Yang, Pan, Pan, & Zhang, 2021)	Identify and categorize uncertainties affecting the offsite logistics of high-rise modular	Literature review and questionnaire survey related to investigation of sources of uncertainties affecting offsite logistics.

	building projects in high-density cities.	

Literature Review

Features and Process of Modular Construction Supply Chain Management

Unlike the traditional supply chain structure, it's not the direct delivery of raw materials from suppliers to the construction sites that constructs the MCSCM, but a series of transportation among manufacturing facilities, warehouses of prefabrication components, and module distribution centers (Hsu, Angeloudis, & Aurisicchio, 2018). What's more, as supply chain is an integration of multiple dynamic systems interacting with each other, careful design and coordination are of great necessity to ensure the efficiency of logistics. Based on the evidence from literature, several features about MCSCM could be summarized (see Table 2).

Table 2

Features of MCSCM

Features	Reasons	Source
Cost effective	Reduced raw material transportation. No need for on-site assembly. Reduced vulnerability to weather extremes.	(CII, 2011) (Sun et al., 2020) (Hsu, Aurisicchio, & Angeloudis, 2019)
Lean concept applicable	Good affinity with manufacturing industry. Standardized with certain level of customization.	(Winch, 2003) (Innella et al., 2019)
Hierarchical	Different levels of completion exist among prefabricated components.	(Ramaji & Memari, 2016)
Resource predictable	Raw Materials are prefabricated into modules, easier to estimate. Labor's working performance is insensitive to single project demands, easier to estimate labor cost. Reduced on-site materials waste due to manufacturing accuracy as well as controlled environment Scheduling is simply based on assembly of modules, less complex than assembling building systems directly.	(Hsu et al., 2019) (Sun et al., 2020) (J. Lee, Park, Lee, & Hyun, 2019)

In the process of traditional supply chain of a construction project, a total of five stakeholders are usually involved: raw material supplier, equipment manufacturer, material and equipment receiver, on-site assembler, project manager (Vrijhoef & Koskela, 2000). Tracking and managing the supply chain is project-based, leading to schedule delay and resource waste caused by uncertainty of material quantity and complexity of resource distribution. Occasional change orders are also considered as one of the threats to the stability and efficiency of the supply chain management. On the contrary, considered as the combination of prefabrication, standardization, and dimensional coordination, modular construction supply chain is more dynamic and flexible (Innella et al., 2019). Since most of the modules and components are standardized and prepared in the prefabrication factories, some on-site assembly time could be saved, allowing for greater tolerance in scheduling. Although modules are standardized, high level of customization is also accessible in terms of building types, locational, and economic situations. Therefore, the whole system of MCSCM should be divided into clusters and categorized into different groups for better customization to meet the requirements of different building owners.

Risk Factors of Modular Construction

Generally, while considering factors that determine the success and suitability of adopting modular construction projects, many researchers agree that local social, legal, and environmental conditions are to be considered (Abdul Nabi & El-adaway, 2020; Sing, Chan, Liu, & Ngai, 2021; Wuni, Shen, & Osei-Kyei, 2019). As Azhar, Lukkad, and Ahmad (2012) categorizes 13 groups of factors that could contribute to the success of modular construction, among which "owner's willingness" and "early and effective project management" are stated to be the top 2 factors. Besides, Wuni et al. (2019) also conducted a comprehensive literature review stating that the availability of skilled labor force and management teams are of great significance, and Choi et al. (2019) summarizes the most recognized barriers for modular constructions in modern areas are conditional site access, limited on-site space, transportation convenience and labor availability. Also, based on the research by Yang, Pan, Pan, and Zhang (2021), source of uncertainties for MCSCM could be categorized into four groups: manufacturing process uncertainties (MPU), demand for module uncertainties (DMU), module supply uncertainties (MSU), and planning and controlling uncertainties (PCU). MPU refers to the detailed internal process within the offsite logistics, DMU includes the owner's, designer's and contractor's requirement for modules, MSU covers the supply of raw materials for building modules and components, and PCU focuses more on the coordination and scheduling of logistics (Yang et al., 2021). Here is a table summarizing the specific risk and contributing factors of each group (see Table 3).

Table 3

Specific risks and contributing factors of each MCSCM group

Group	Specific Risks	Quantitative Risk Factors	Sources
MPU	Lack of skilled workforce, ineffective manufacturing design, long-distance transportation, machine problems.	Number of labors, machine inspection times, distance between factories, warehouses, and sites.	(Yu, Al-Hussein, Al-Jibouri, & Telyas, 2013)
DMU	Late design changes, speed of module installation.	Number of change orders, time for preparing modules.	(Rahman, 2014; Zhai, Fu, Xu, & Huang, 2019)
MSU	Accuracy of material quantity, timely delivery of the materials	Percentage of accurate material supply, delay time of materials.	(Li, Al-Hussein, Lei, & Ajweh, 2013)
PCU	Incorrect control actions, inadequate quality control systems, poor stakeholder communication, inadequate technology failures.	Data loss, waste caused by lack of communication	(Sun et al., 2020; Vrijhoef & Koskela, 2000)

Importance of Classifying Modular Construction Supply Chain

The classification of supply chain based on project features is both theoretically and practically significant (Frohlich & Dixon, 2001), so does MCSC. As Rosenfeld (1996) proposes two kinds of networks for supply chain management. One is called "hard networks" where different firms and organizations join forces and collaborate for better producing, purchasing and operating the whole system. The other one is called “soft networks”, where firms form to groups to solve common problems, share information and obtain new abilities and skills. So, to achieve the best efficiency of SCM, the whole system should be stratified and classified based on land cost, labor cost, component type, and other criterion, in order to manage different types of “buyer-supplier” relationship and organize the products and materials in a better way.

Different from traditional supply chain in which materials are directly transported to the construction site, MCSCM simplifies the work on site but challenges the project managers with organizing the transportation and storing of prefabricated components and modules (Ahmed, Kristal, Pagell, & Gattiker, 2017). Normally, most of the prefabricated components for modular construction are linear members (beams, lintels, columns), rigid structural frames, roofing and flooring components, doors and windows, and wall panels because these components are standardized easy for transportation, dismantling and assembling (Admin, 2021). Additionally, a great number of Mechanical, Electrical and Pumping (MEP) components are also prefabricated and preinstalled for transportation.

According to the survey from Jones (2020), the most frequent building types for prefabrication and modular construction are healthcare facilities, hotels and motels, college building and dormitories, high-rise offices and schools. All of those building types are usually located in the dense population area where land price and labor cost are higher, especially in metropolitan areas. Therefore, in order to reduce the unnecessary cost for on-site assembly and transportation of materials, warehouses and factories for modular construction are constructed and distributed in the rural area, and the design of warehouse locations and clustering of warehouses to minimize the transportation time and cost is the goal for classifying MCSCM.

Discussion – Future improvements of Modular Construction Supply Chain

Due to continuous flow of globalization and product specialization, a new term, “supply chain management 2.0”, has emerged to demonstrate both the changes in the supply chain management itself but also the changes in the processes, technologies and tools. Based on the literature review, potential solutions for mitigating the impacts of risk factors could be summarized as: reasonable allocation of workforce based on labor availability and cost, better supply chain mapping based on project types, flexible scheduling strategy based on supply and demand, and monitoring of transported products and modules based on real-time data transmission and response.

Workforce Allocation

Workforce planning and distribution in terms of skills and wages is directly affecting the budget of the project (Arashpour, Wakefield, Blismas, & Minas, 2015). As Nasirian, Abbasi, Cheng, and Arashpour (2022) assert that we should think about workforce distribution from both managerial perspective and technical perspective. Since modular supply chain could be divided into three stages as: materials to prefabrication manufacturing, prefabricated components to module assembly, assembled modules to the construction site, each stage requires workforce with different skills and expertise. In the previous supply chain, workers are supposed to collaborate together on the field to finish necessary jobs, leading to increase in labor cost and project duration since work sequence exist and the project schedule is process-based. On the comparison, the workforce for future supply chain is distributed into multiple locations including factories, warehouses, and distribution points based on the local labor costs and land cost in order to lower the budget. Research by Nasirian, Arashpour, and Abbasi (2019) also conduct an investigation about construction workforce planning and asserts that skilled-based workforce planning is the matured approach for allocating labor resources between construction and manufacturing industry.

Supply Chain Mapping

Because supply chain mapping is defined as a methodology to increase the transportation efficiency, provide visibility and reduce disruption, it's responsible for the duration of module transportation and distribution to various construction sites. Normally, in previous MCSCM, several lines are established directly between manufacturing factories and construction sites to ease the transportation process and reduce potential risks. However, as construction sites are located in different areas with different traffic conditions, population density, and freight shipping fees, it's reasonable to make some alternations to the mapping design considering these factors.

Scheduling Strategy

As mentioned before, current project scheduling is process-based, meaning that the workflow could progress only when previous steps are finished. However, for future modular construction, the project workflow will be project-based. In other words, the arrangement of module transportation and distribution is based on project needs rather than assembling process, allowing for more flexibility of the scheduling and also reduce the time wasted by waiting for previous work to be done.

Transportation Monitoring

One of the most significant issues for all the supply chain management is quality control of the product during the transportation process, especially for modular construction since components are supposed to be assembled separately in different factories. Thus, digital twin assistance could be applied to monitor real-time logistics and simulate the whole process for determining potential risks, since digital twin means a virtual replica of the physical module in the real world (D. Lee & Lee, 2021). Within the digital twin, Building Information Modeling (BIM) are applied to store all the data concerning details of the logistics process, warehouse, module assembly places, and the construction sites; Internet of Things (IoT) sensors can be utilized in factories, warehouses, trucks, and module components to mark and locate the real-time location and condition of each component. Additionally, with the aid of Geographic Information System, the marked locations could be connected with the global mapping system, enabling the optimization process of the supply chain routes.

Conclusion and Future Research

In this paper, a literature review concerning modular construction and its supply chain management is conducted, demonstrating the features and basic process of MCSCM, risk factors along the supply chain, as well as the classification of MCSCM in terms of project types and component categories. Later in the discussion part, four types of suggestions corresponding to each risk are proposed to improve the current supply chain system from the perspective of workforce, scheduling, routes mapping and process monitoring for MCSCM. Future research can focus on conducting experiments by applying the suggested recommendations in the four categories in real modular projects and conducting case study analysis to demonstrate and quantify the benefits in terms of reduction in project duration and cost. Also, the estimation of modular construction market in the next 15 years based on the increasing population and different building types of demand is considered as another meaningful topic for proactive approach to emerging MCSCM.

References

Abdul Nabi, M., & El-adaway, I. H. (2020). Modular construction: Determining decision-making factors and future research needs. *Journal of Management in Engineering, 36*(6), 04020085. [DOI: 10.1061/(ASCE)ME.1943-5479.0000859]

Azhar, S., Lukkad, M., & Ahmad, I. (2012). *Modular v. stick-built construction: Identification of critical decision-making factors.* Paper presented at the 48th Annual Conference of Associated Schools of Construction.

Baldwin, A., Poon, C.-S., Shen, L.-Y., Austin, S., & Wong, I. (2009). Designing out waste in high-rise residential buildings: Analysis of precasting methods and traditional construction. *Renewable Energy, 34*(9), 2067-2073. [DOI: 10.1016/j.renene.2009.02.008]

Choi, J. O., Chen, X. B., & Kim, T. W. (2019). Opportunities and challenges of modular methods in dense urban environment. *International journal of construction management, 19*(2), 93-105. [DOI: 10.1080/15623599.2017.1382093]

CII. (2011). Transforming modular construction for the competitive advantage through the adaptation of shipbuilding production processes to construction. In: Construction Industry Institute, Univ. of Texas at Austin Austin, TX.

Council, N. R. (2009). *Advancing the competitiveness and efficiency of the US construction industry*: National Academies Press.

Doran, D., & Giannakis, M. (2011). An examination of a modular supply chain: a construction sector perspective. *Supply Chain Management: An International Journal, 16*(4), 260-270. [DOI: 10.1108/13598541111139071]

Enshassi, M. S., Walbridge, S., West, J. S., & Haas, C. T. (2019). Integrated risk management framework for tolerance-based mitigation strategy decision support in modular construction projects. *Journal of Management in Engineering, 35*(4), 05019004. [DOI: 10.1061/(ASCE)ME.1943-5479.0000698]

Ferdous, W., Bai, Y., Ngo, T. D., Manalo, A., & Mendis, P. (2019). New advancements, challenges and opportunities of multi-storey modular buildings–A state-of-the-art review. *Engineering Structures, 183*, 883-893. [DOI: 10.1016/j.engstruct.2019.01.061]

Hsu, P.-Y., Angeloudis, P., & Aurisicchio, M. (2018). Optimal logistics planning for modular construction using two-stage stochastic programming. *Automation in Construction, 94*, 47-61. [DOI: 10.1016/j.autcon.2018.05.029]

Hsu, P.-Y., Aurisicchio, M., & Angeloudis, P. (2019). Risk-averse supply chain for modular construction projects. *Automation in Construction, 106*, 102898. [DOI: 10.1016/j.autcon.2019.102898]

Innella, F., Arashpour, M., & Bai, Y. (2019). Lean methodologies and techniques for modular construction: chronological and critical review. *Journal of Construction Engineering and Management, 145*(12), 04019076. [DOI: 10.1061/(ASCE)CO.1943-7862.0001712]

Lee, D., & Lee, S. (2021). Digital twin for supply chain coordination in modular construction. *Applied Sciences, 11*(13), 5909. [DOI: 10.3390/app11135909]

Lee, J., Park, M., Lee, H.-S., & Hyun, H. (2019). Classification of modular building construction projects based on schedule-driven approach. *Journal of Construction Engineering and Management, 145*(5), 04019031. [DOI: 10.1061/(ASCE)CO.1943-7862.0001656]

Li, H. X., Al-Hussein, M., Lei, Z., & Ajweh, Z. (2013). Risk identification and assessment of modular construction utilizing fuzzy analytic hierarchy process (AHP) and simulation. *Canadian Journal of Civil Engineering, 40*(12), 1184-1195. [DOI: 10.1139/cjce-2013-0013]

Liu, J., & Lu, M. (2018). Constraint programming approach to optimizing project schedules under material logistics and crew availability constraints. *Journal of construction engineering and management, 144*(7), 04018049. [DOI: 10.1061/(ASCE)CO.1943-7862.0001507]

Markets, R. a. (2020). Modular construction market—Growth, trends, and forecast (2020-2025). Retrieved from https://www.researchandmarkets.com/reports/4515000/modular-construction-market-growth-trends

O'Connor, J. T., O'Brien, W. J., & Choi, J. O. (2014). Critical success factors and enablers for optimum and maximum industrial modularization. *Journal of Construction Engineering and Management, 140*(6), 04014012. [DOI: 10.1061/(ASCE)CO.1943-7862.0000842]

O'Connor, J. T., O'Brien, W. J., & Choi, J. O. (2016). Industrial project execution planning: Modularization versus stick-built. *Practice periodical on structural design and construction, 21*(1), 04015014. [DOI: 10.1061/(ASCE)SC.1943-5576.0000270]

Rahman, M. M. (2014). Barriers of implementing modern methods of construction. *Journal of Management in Engineering, 30*(1), 69-77. [DOI: 10.1061/(ASCE)ME.1943-5479.0000173]

Ramaji, I. J., & Memari, A. M. (2016). Product architecture model for multistory modular buildings. *Journal of Construction Engineering and Management, 142*(10), 04016047. [DOI: 10.1061/(ASCE)CO.1943-7862.0001159]

Sing, M., Chan, J., Liu, H., & Ngai, N. N. (2021). Developing an analytic hierarchy process-based decision model for modular construction in urban areas. *Journal of Engineering, Design and Technology*(ahead-of-print). [DOI: 10.1108/JEDT-05-2021-0242]

Sun, Y., Wang, J., Wu, J., Shi, W., Ji, D., Wang, X., & Zhao, X. (2020). Constraints hindering the development of high-rise modular buildings. *Applied Sciences, 10*(20), 7159. [DOI: 10.3390/app10207159]

Vrijhoef, R., & Koskela, L. (2000). The four roles of supply chain management in construction. *European journal of purchasing & supply management, 6*(3-4), 169-178. [DOI: 10.1016/S0969-7012(00)00013-7]

Winch, G. (2003). Models of manufacturing and the construction process: the genesis of re-engineering construction. *Building Research & Information, 31*(2), 107-118. [DOI: 10.1080/09613210301995]

Wuni, I. Y., Shen, G. Q., & Osei-Kyei, R. (2019). Scientometric review of global research trends on green buildings in construction journals from 1992 to 2018. *Energy and buildings, 190*, 69-85. [DOI: 10.1016/j.enbuild.2019.02.010]

Yang, Y., Pan, M., Pan, W., & Zhang, Z. (2021). Sources of uncertainties in offsite logistics of modular construction for high-rise building projects. *Journal of Management in Engineering, 37*(3), 04021011. [DOI: 10.1061/(ASCE)ME.1943-5479.0000905]

Yu, H., Al-Hussein, M., Al-Jibouri, S., & Telyas, A. (2013). Lean transformation in a modular building company: A case for implementation. *Journal of Management in Engineering, 29*(1), 103-111. [DOI: 10.1061/(ASCE)ME.1943-5479.0000115]

Zhai, Y., Fu, Y., Xu, G., & Huang, G. (2019). Multi-period hedging and coordination in a prefabricated construction supply chain. *International Journal of Production Research, 57*(7), 1949-1971. [DOI: 10.1080/00207543.2018.1512765]

Spatial Discrepancies between Close-Range Photogrammetry and Terrestrial-LiDAR Models

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This article investigates spatial discrepancies existing between two simple, close-range photogrammetry (CRP) models and a terrestrial light detection and ranging (T-LiDAR) model. The latter is more accurate and serves as benchmark. The commonly modeled zone is a six-acre commercial property. All three models were georeferenced in the same coordinate system before acquiring spatial coordinates of 50 common points from each of them. Two models were produced via CRP, employing Agisoft's Metashape Professional software, and one, the benchmark model, was generated using Leica Geosystems' C10 scanner. This laser-based model used Leica's Visual Alignment procedure for registration purposes. This approach is not the most accurate available today, however, it requires minimal target acquisitions and saves considerable time in the field. One of the CRP models was built with pictures taken from an UAV flying at an approximate 76-ft altitude over ground level. The second CRP model was produced with pictures taken from a 116-ft altitude. Fifty positions and 1,225 distance discrepancies were calculated for each CRP model with respect to the same points and distances acquired from the T-LiDAR model. The compared distances ranged from 0.02 to 415.50 ft. A statistical analysis of those discrepancies is presented in this paper.

Key Words: Close-Range Photogrammetry, LiDAR, Distance Discrepancy

Introduction

Nowadays, CRP via Unmanned Aerial Vehicles (UAVs or 'drones') is often employed in the Architectural, Engineering and Construction (AEC) industry for a variety of useful purposes. This low-cost alternative to 3D laser scanning is becoming commonly used in construction related projects, including virtual surveying, capture of as-built conditions for predesign/design activities, monitoring of construction progress, determination of pay quantities, etc. More than a decade ago, Remondino et al. (2011) already presented an overview of existing UAV systems, especially those employed in geomatics applications. They described the status and future perspectives of UAV photogrammetry for mapping and 3D modeling. More recently, Li and Liu (2019) indicated numerous current applications of the use of drones in the construction industry, especially in land surveying, logistics, on-site construction, maintenance and demolition. Luhmann (2019) described recent developments in CRP indicating that "In industrial applications, the verification of the achieved accuracy with respect to accepted guidelines is most important. In most cases, standardized characteristics such as the maximum length measurement error have to be reported…" Even though CRP is now ubiquitous, not all users know the technical and scientific aspects of this technique or even the actual spatial accuracies that could be attained in their resulting 3D models. There are numerous factors contributing to those accuracies. Two significant ones are the quality/resolution of the employed cameras and the altitude from where pictures are taken. They are critical in determining the size of a detail that could be distinguished in a single pixel. The estimation of the attained spatial accuracies in the final CRP models, when using currently affordable drones, has motivated the completion of the work reported here.

The objective of this study is to determine statistical discrepancies in distances extracted from three different models of the same existing spatial conditions. Two of these virtual models are CRP ones and their extracted distances were compared against a more accurate T-LiDAR model, which served as benchmark. The generation of the resulting CRP models require minimum knowledge of CRP techniques, as the user only needs to know how to fly an UAV and how to employ a commercially available CRP software package.

The selected modeled area is a 6-acre commercial property, Fusion Gymnasium, in Statesboro, GA. One of the CRP models was built with pictures taken at an average altitude of 76-ft over the ground and is herein referred to as the 76'-CRP model. The other CRP model was produced with pictures taken from a 116-ft altitude and is herein referred to as the 116'-CRP model. Since both CRP models used the same camera and resolution, it was expected that the low-altitude one will be able to distinguish more details and, consequently, be more accurate than the high-altitude model.

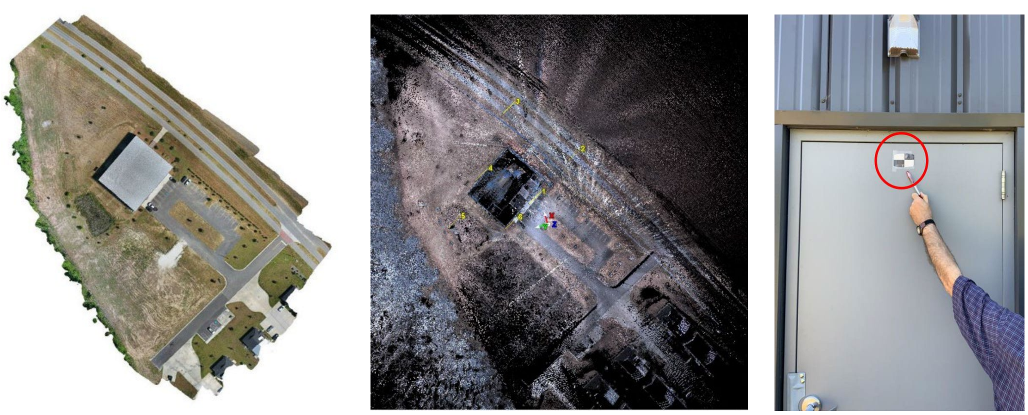
The selected T-LiDAR benchmark model employed 47 scans and was generated via a registration procedure known as Leica's Visual Alignment. This approach is less accurate than a target-based registration, but it requires minimum target acquisition in the field and allows for a faster completion of the required field scans. Nevertheless, Visual Alignment requires more human intervention and data processing time in a computer laboratory than a target-based registration process. Several recent studies have completed distance-discrepancy analyses involving T-LiDAR models. They include the work by Maldonado et al. (2020) where the discrepancy between georeferenced and non-georeferenced models were investigated. A year ago, Maldonado et al. (2021) estimated the error introduced by georeferencing a point-cloud model via an accurate closed-traverse survey. Additionally, recently, Maldonado et al. (2022) analyzed distance discrepancies in T-LiDAR models georeferenced via Static GNSS vs Rapid RTK GNSS.

Instruments and Methodology

This work employed four main instruments. They are shown in Figure 1 and their characteristics are briefly described in this paragraph: (1) A 1-sec robotic, total-station device from Leica Geosystems, TRCP 1201+ R1000. Its manufacturer indicates (Leica 2021) this instrument has a range of 1,500 m (~1,640 yd) when used with a 360° reflector prism, under light haze with visibility of 20 km (~21,900 yd). In reflector mode, the standard deviation σ of its error, for a single-distance measurement, is $\sigma = 1$ mm+1.5 ppm×(distance < 3000 m). In US Customary units, that accuracy is equivalent to $\sigma = 0.04$ in+1.5 ppm×(distance < 3,281 yd). Its angular accuracies are 1 arcsecond for horizontal and vertical angles. This total-station instrument was used with a 360° reflector prism, Leica's GRZ4, to complete a closed-traverse procedure. This resulted in the establishments of six fixed, ground, control points within the area to be modeled. (2) A laser-based scanner, Leica Geosystems' ScanStation C10, was employed to generate a 3D point-cloud model of the selected area and structure for comparison purposes. According to Leica Geosystems (Leica 2022), this scanner has a position accuracy of 6 mm (0.24 in) and measurement accuracy of 4 mm (0.16 in), both are 1σ at 1-50 m range (1.1-54.7 yd range). This scanner has a dual-axis compensator with horizontal and vertical angular accuracies of 12 seconds. Its scanning range is 300 m (328 yd) at 90% albedo and 134 m (146.5 yd) at 18% albedo. Its maximum scanning rate is 50,000 points per second. (3) An UAV from Da-Jiang Innovations (DJI) was used to capture the pictures leading to the generation of two 3D, close-range, photogrammetric models. This small commercially available drone is the DJI Mavic 2 Pro. It weighs 907 grams and carries a 20-megapixel camera, mounted on a three-axis gimbal for stabilization purposes. Additional specifications can be found at DJI's website (DJI, 2022). (4) A Topcon AT-B2 Automatic Level instrument was employed to obtain differential elevations among the six fixed, ground points used to georeference the resulting three virtual models of this project. Topcon Corporation (Topcon, 2022) indicates that this device has a 32x-magnification eyepiece and a dampened compensator able to level the line of sight within a range of ±15 arcminutes, with a setting accuracy of 0.3 arcsecond. Additionally, Topcon specifies that this device, when used with a leveling rod without micrometer, can complete a 1-km, double-run, leveling procedure with an accuracy of 0.7 mm (0.03 in).

(a) (b) (c) (d) (e)

Figure 1. Employed devices: (a) DJI's Mavic 2 Pro; (b) Leica's Robotic Total Station TCRP 1201+ R1000, (c) & (d) Leica's ScanStation C10, (e) Topcon's AT-B2 Auto Level



(a) (b) (c)

Figure 2. Plan Views: (a) Photo-based model from 116 ft; (b) 3D, T-LiDAR Model (North is approximately upward in both pictures); (c) Example of sticker to identify a secondary point.

In this study, the modeled commercial property encompassed 6 acres. It included a gymnasium building, its parking lot, and surrounding grassy zones (see Figure 2). Three models were generated to compare their relative accuracies: 76'-CRP, 116'-CRP, and T-LiDAR models. The employed methodology involved ten different tasks:

(I) Initially, six ground control points were established within the site. Their spatial coordinates where accurately determined, within a selected local system of reference, via a closed-traverse procedure. This approach resulted in an initial horizontal error of closure of 0.023 ft and in a longitudinal precision of 1 in 31,397. The local system of reference was selected by assigning the following coordinates to vertex 1: Easting = 400.000 ft, Northing = 800.000 ft, Elevation = 100.000, and by selecting an arbitrary value, 60°, for azimuth 1→2. Table 1 shows the final balanced coordinates of all 6 ground control points. Later, these coordinates were employed to georeference, into the same common system, the resulting three virtual models.

Table 1

Balanced Local Coordinates of Ground Control Points via Closed Traverse

Vertex	EASTING X (ft)	NORTHING Y (ft)	ELEVATION Z (ft)
1	400.000	800.000	100.000
2	500.800	858.196	102.457
3	405.187	987.789	100.936
4	312.529	877.556	99.561
5	230.620	803.535	96.391
6	339.238	766.424	99.156

Tasks **(II)-(V)** are related to the generation of the two CRP models: **(II)** Before scanning or taking pictures, more than 100 highly visible, black-&-white stickers (~ 10 cm × 6.5 cm each) where placed on walls, doors, window frames, light posts, sidewalks, pavements, mailbox, and other objects contained within the area to be modeled. See sample sticker on Figure 2c. These points are herein referred to as Secondary Points. Their locations were to be identified later, within each of the three models, to extract their coordinates and distances between them. **(III)** In this task, the Mavic 2 Pro UAV was flown over the site by our Lab Manager, Mr. Shawn Jackson, who is a licensed Remote Pilot by the Federal Aviation Administration. The drone was programmed to automatically take necessary overlapping pictures. Two different sets of pictures were acquired, one from an average 76' altitude, over the ground, and the other from an averaged 116' altitude. These altitudes were reported during data processing by the employed CRP software package. Task **(IV)** consisted in using Agisoft's Metashape Pro software (version 1.7.1 built 11797), in the BEaM laboratory, to generate the 76'-CRP and the 116'-CRP virtual models, one from each set of pictures. During task **(V)**, the resulting two 3D photo-based models were georeferenced into the same selected local coordinate system. For this purpose, within each virtual model, markers were placed on identified locations of the corresponding control points listed in Table 1. Then, the coordinates of these control points were imported into the CRP models to define scaling bars within each of them. The lengths of these bars were pythagorically calculated from the coordinates in Table 1. A few of the characteristic parameters for the resulting 76'-CRP and 116'-CRP models, including RMSE values, are presented in Tables 2 and 3, respectively.

Tasks **(VI)**-**(VIII)** are associated with the generation of the T-LiDAR model: Task **(VI)** consisted in laser scanning the site with Leica's ScanStation C10. A total of forty-five (45) exterior and two (2) interior scans were completed to cover the selected area. This took approximately 35-45 minutes per scan. In Task **(VII)**, unwanted noise (i.e., solar beams, and vehicular/pedestrian traffic) was removed from each scan. During this task, the Leica's Visual Alignment registration (stitching) procedure was employed to build an initial, non-georeferenced point-cloud model. This scheme consisted of stitching two neighboring scans at a time to grow and build a fully stitched point-cloud, the T-LiDAR model. This approach saved considerable scanning time in the field but increased the post-processing time in the laboratory. This manual stitching procedure is less accurate than a target-based registration which requires more time in the field. The 6 ground control points were scanned by using white, spherical, six-inch-diameter targets, placed on poles of known heights, over their respective ground nails. All scans were completed at medium resolution which corresponds to a separation of 10 cm (~3.94 in) between scanned points when they are at 100 m (~328.1 ft) from the scanner. During task **(VIII)** the full T-LiDAR model was georeference in the same local coordinate system used by the CRP models. This required to import the coordinates of the 6 ground control points from a text file which served as an additional small scan file (containing only those 6 points). Then, their locations were matched via a least-square scheme with those of the same points already scanned and included in the point cloud.

Table 2

Characteristics of the Two Photo-Based Models (According to the Metashape Software)

Flying Altitude (ft)	Number of Images	Aligned Cameras	Covered Area yd^2	Ground Resolution ft/pix	Control Points	Check Points	Scale Bars
76	600	589	27,600	0.0165	6	50	6
116	464	461	33,300	0.0253	6	50	6

Table 3

Root Mean Square Errors Reported by Metashape for 6 Control Markers and 50 Check Points

	X (ft)	Y (ft)	Z (ft)	XY (ft)	Total (ft)
CRP Model	(6) Control Markers				
75-ft	0.242	0.168	0.266	0.294	0.397
116-ft	0.234	0.156	0.192	0.341	0.384
CRP Model	(50) Check Points				
75-ft	0.107	0.101	0.219	0.148	0.264
116-ft	0.227	0.214	0.226	0.385	0.915

Tasks **(IX)** and **(X)** lead to the statistics of discrepancies in lengths extracted from the finalized 3 models: Task **(IX)** involved all 3 georeferenced virtual models, 76'-CRP, 116'-CRP, and T-LiDAR. It consisted in identifying 50 auxiliary points, common to all 3 models. The spatial coordinates of these points were extracted 3 times, one from each model. Even though these 50 points were the same in all 3 final virtual models, their coordinates showed small discrepancies from one model to another. During task **(X)**, the distances between each auxiliary point and the remaining 49 auxiliary points were pythagorically determined within the same model. This resulted in a total of 1,225 non-repeated distances from each model. This was done 3 times, one per model. Then, these distances were compared to determine the statistics of the discrepancies of each CRP model with respect to the same distances extracted from the T-LiDAR model.

Results

The above methodology led to the identification of 50 common auxiliary points in all 3 resulting virtual 3D models. For each auxiliary point, 3 sets of coordinates were acquired. One set from each of the 3 models (76'-CRP, 116'-CRP, and T-LiDAR). All discrepancies were determined with respect to the more accurate model, T-LiDAR, which served as benchmark. That is, the position discrepancies were calculated by vectorially subtracting the fifty T-LiDAR positions from the corresponding fifty 76'-CRP positions and also from the fifty 116'-CRP positions. This resulted in two position discrepancies for each of the fifty auxiliary points, one for the 76'-CRP model and one for the 116'-CRP model, both versus the T-LiDAR model. Their statistics are presented in Table 4, where it can be observed that the mean values of the discrepancies are not zero. Therefore, the standard deviation of the population (STD_P) or of the sample (STD_S) do not coincide with their respective root mean square values (RMSV).

Since the RMSV is a measure of the magnitude of a set of numbers, which in this case are position discrepancies, we focused on this parameter to compare the position discrepancies of both photo-based models with respect to the LiDAR model.

Table 4

Statistics of two types of discrepancies: (a) Position discrepancies of 50 auxiliary points. (b) Distance discrepancies among those 50 points (1225 non-repeated distances).

Statistic Function	76'-CRP Model vs T-LiDAR Model		116'-CRP Model vs T-LiDAR Model	
	Position Discrepancies (ft)	Distance Discrepancies (ft)	Position Discrepancies (ft)	Distance Discrepancies (ft)
Max =	1.955	1.798	1.997	1.769
Min =	0.000	-1.473	0.037	-1.547
Mean =	0.364	0.165	0.470	0.329
Median =	0.301	0.150	0.331	0.310
STD_P =	0.330	0.299	0.372	0.428
STD_S =	0.333	0.299	0.376	0.428
RMSV =	0.491	0.341	0.599	0.540

The RMSV of the position discrepancy for the 76'-CRP model is $RMSV_{76\text{-ft}}$ = 0.49 ft, whereas for the 116'-CRP model, is $RMSV_{116\text{-ft}}$ = 0.60 ft. This is consistent with the expected result. That is, the lower-altitude close-range photogrammetric model should present less error with respect to the LiDAR model than the higher-altitude one.

Figures 3 and 4 show the discrepancy in the 1,225 non-repeated distances among the fifty auxiliary points. Their lengths ranged from 0.015 ft to 415.504 ft. Figure 3 shows the distance discrepancies between the 76'-CRP and LiDAR models. Figure 4 depicts the distance discrepancies between the 116'-CRP and LiDAR models.

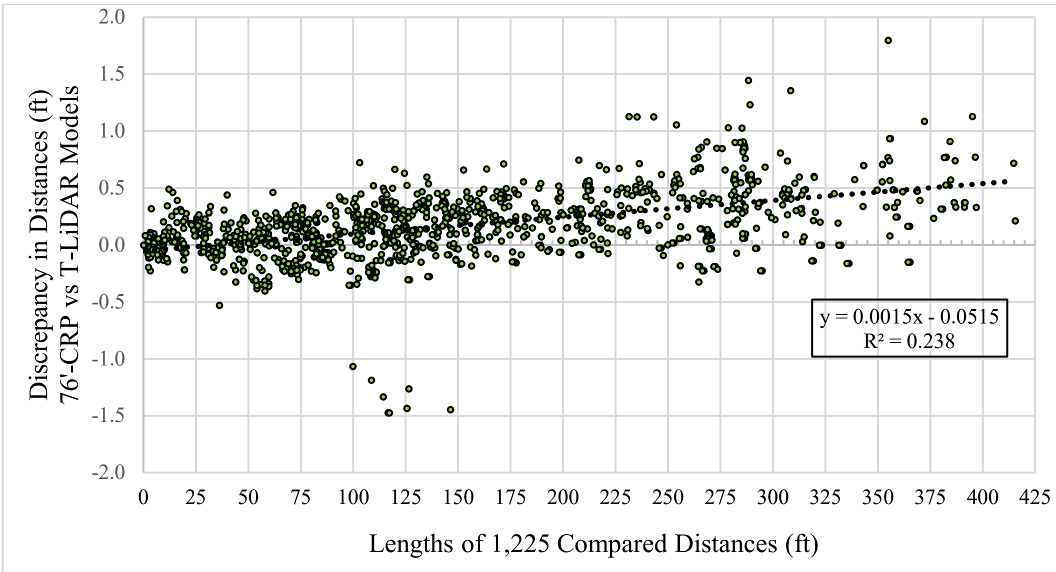


Figure 3. Discrepancies in lengths. T-LiDAR Distances Subtracted from 76'-CRP Distances

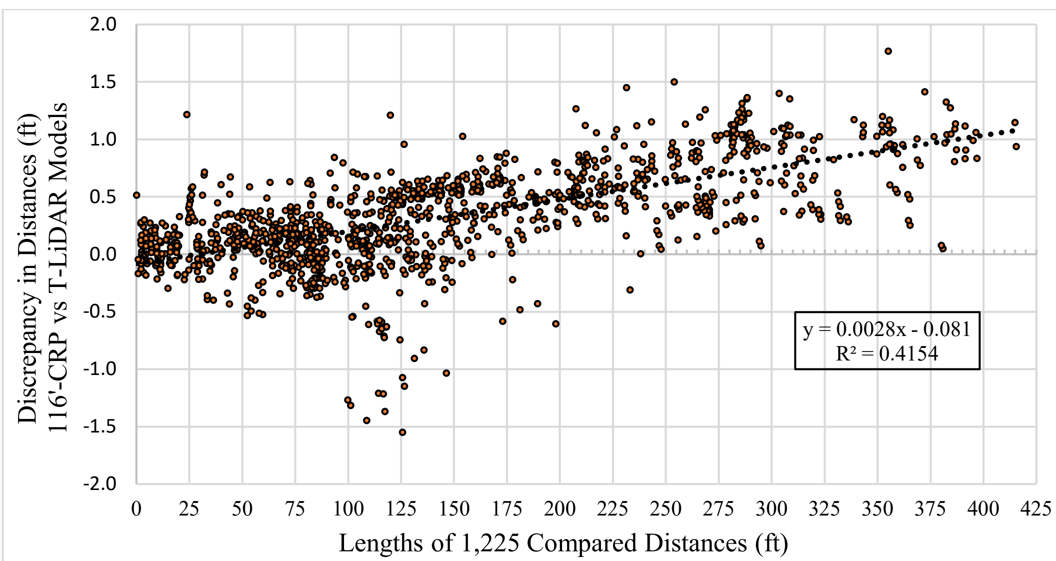


Figure 4. Discrepancies in lengths. T-LiDAR Distances Subtracted from 116'-CRP Distances

Both figures, 3 and 4, show a trend line and include the expressions of their corresponding linear regressions along with their respective coefficients of determination (R^2 values). For the 76’-CRP model, $R^2 \approx 24\%$, whereas for the 116’-CRP model $R^2 \approx 42\%$. This coefficient is an indication of the extent that the variance of distance discrepancies is explained by the variance in the magnitude of the lengths of those distances. Figure 5 shows pictures of two finalized models.

(a) (b)

Figure 5. Views of Final Models: (a) 116’-CRP Model, and (b) T-LiDAR Model

Final Remarks and Conclusions

This work consisted in generating 3 different virtual 3D models of the same existing conditions on a 6-acre commercial area and in determining their spatial discrepancies. For this, the Cartesian coordinates of the same 50 points were acquired from each of the 3 different models. Two models were produced via CRP and one, the most accurate, was generated using a T-LiDAR scanner, via a semi-manual registration procedure, Leica Geosystems’ Visual Alignment. One of the CRP models was built with pictures taken from a 76-ft-average altitude flight above ground. The second CRP model was produced with pictures taken from an approximate altitude of 116 ft. Fifty positions and 1,225 non-repeated distances among them were considered to calculate the spatial discrepancies of each CRP model with respect to the same points and distances acquired from within the T-LiDAR model. The 1,225 compared distances ranged from 0.015 to 415.50 ft. Since several points and distances presented large discrepancies, their coordinates were double checked and reacquired, but remained with the same original values. Therefore, those few large discrepancy magnitudes stayed as valid data in this study.

After completion of the statistical analyses, the following remarks and conclusions are presented:

1. The largest discrepancies of the CRP models, with respect to the T-LiDAR model, are associated to points acquired in excessively deformed areas of the resulting photogrammetric models.

2. Regarding point-position measurements, the 76’-CRP model is 1.22 times more precise than the 116’-CRP model. This factor was determined by using the following ratio of RMSVs:
$$\frac{RMSV_{Position\ Discrp.}\ of\ CRP\ Model_{116-ft}}{RMSV_{Position\ Discrp.}\ of\ CRP\ Model_{76-ft}} = \frac{0.599\ ft}{0.491\ ft} = 1.22$$

3. Regarding distance measurements, the 76’-CRP model is 1.58 times more precise than the 116’-CRP model. This factor was determined by using the following ratio of RMSVs:
$$\frac{RMSV_{Distance\ Discrp.}\ of\ CRP\ Model_{116-ft}}{RMSV_{Distance\ Discrp.}\ of\ CRP\ Model_{76-ft}} = \frac{0.540\ ft}{0.341\ ft} = 1.58$$

4. In Figures 3 and 4 it is observed that the discrepancies in the distances are becoming more positive as the magnitude of the measured lengths increases. This trend is captured by the linear regressions included in those figures. That is, the distance discrepancies of the 116'-CRP model (with respect to the T-LiDAR model) tend to increase more with the magnitude of the measured lengths than the distance discrepancies of the 76'-CRP model (with respect to the T-LiDAR model).

References

DJI (2022), Mavic 2 Specs. Available at the below link, accessed on October 29, 2022: https://www.dji.com/mavic-2/info#specs

Li, Y., & Liu, C. (2019). Applications of multirotor drone technologies in construction management. International Journal of Construction Management, 19(5), 401–412.

Leica (2021), Leica TPS 1200 Series Technical Data (2022). 16 pages. Available at the below link, accessed on Oct 29, 2022: https://osdc.ca/wp-content/uploads/2015/07/TPS1200_TechnicalData.pdf

Leica (2022), Leica ScanStation C10. The All-in-One Laser Scanner for Any Application. Available at the below link, accessed on Nov 14, 2021: https://lib.store.yahoo.net/lib/yhst-141816440267150/Leica-ScanStation-C10-DataSheet.pdf

Luhmann, T. (2019). Recent Developments in Close-Range Photogrammetry. GIM International Magazine, February 14, 2019. Available at the below link, accessed on December 15, 2022: https://www.gim-international.com/content/article/recent-developments-in-close-range-photogrammetry

Topcon (2022), AT-B Series Auto Level, Available at the below link, accessed on Oct 29, 2022: https://www.topcon.co.jp/en/positioning/products/pdf/AT-B2_AT-B3A_AT-B4A_E.pdf

Maldonado, G.O., Maghiar, M., Tharp, B., and Patel, D., (2020). Point-Cloud Models of Historic Barns – Spatial Discrepancies of Laser Scanning versus Robotic Total Station. ASC 2020 56th Annual ASC International Conference, (Epic Series in Built Environment, Vol 1), pp 292-300.

Maldonado, G.O., Maghiar, M., and Augustine, A., (2021). Comparison of Distance Discrepancies in Georeferenced and Non-Georeferenced Terrestrial LiDAR Models. ASC 2021 57th Annual ASC International Conference, (Epic Series in Built Environment, Vol 2), pp 311-319.

Maldonado, G.O., Ibrahim, U., Purcell, R., Nam, S., and Maghiar, M., (2022). Distance Discrepancies in T-LiDAR, Point-Cloud Models Georeferenced via RTK and Static GNSS. ASC 2022 58th Annual ASC International Conference, (Epic Series in Built Environment, Vol 3), pp 434-442.

Remondino, F., Barazzetti, L., Nex, F., Scaioni, M., and Sarazzi, D., (2011). UAV Photogrammetry for Mapping and 3D Modeling –Current Status and Future Perspectives–. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XXXVIII-1/C22, pp 25-31, September 2011, Zurich , Switzerland.

Fixed Budget-Best Value Procurement Method and Case Studies for Transportation Projects

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As the highway construction industry faces significant challenges in rehabilitating aging infrastructure and meeting growing traffic volumes, delivering projects within available funds becomes far more critical. Fixed budget-best value (FB-BV), also known as "design-to-costs", allows state departments of transportation (DOTs) to generate more amount of work while achieving the best value for dollars expended. This paper aims to investigate practices of FB-BV for highway projects in state DOTs and analyze case studies of FB-BV procurement contracting strategies. This study presents practices and case studies related to FB-BV procurement contracting strategies in four state highway agencies including, Idaho, Michigan, Utah, and Colorado. This paper reviewed the current state of practices in the FB-BV procurement method and identified best practices in utilizing this innovative contracting method. The results showed that defining the basic configuration scope, defining additional scope elements, and establishing rigorous evaluation criteria and their weights are critical for successfully delivering projects with the FB-BV contracting strategy. The findings of this study contribute to the state of knowledge and practice of the FB-BV procurement method and help state DOTs establish an effective process for implementing the FB-BV contracting method under a strict budget.

Key Words: Design Build, Fixed Budget-Best Value, Highway Project, Innovative Project Delivery

Introduction

The highway construction industry in the United States faces significant challenges in rehabilitating aging infrastructure and meeting growing traffic volumes with limited funding. Thus, delivering projects within available funds becomes far more critical in the highway construction industry. Amid the increasing complexity of projects and funding constraints, state departments of transportation (state DOTs) have utilized best-value procurement methods, such as fixed budget-best value (FB-BV), to maximize the value of dollars expended for their projects. The best value-procurement methods can be typically applied to design-build (DB) projects. Figure 1 illustrates the project delivery sequences of traditional and DB project delivery methods. The best value procurement methods can include several evaluation criteria, such as price, schedule, and technical factors, in the request for proposals (RFPs).

With best-value procurement methods, state DOTs can select key factors that match or meet the project's specific requirements (Scott et al. 2006). Based on the key evaluation factors, the state DOT selects the proposal that most closely meets or exceeds the owner's expectations and the project's requirements.

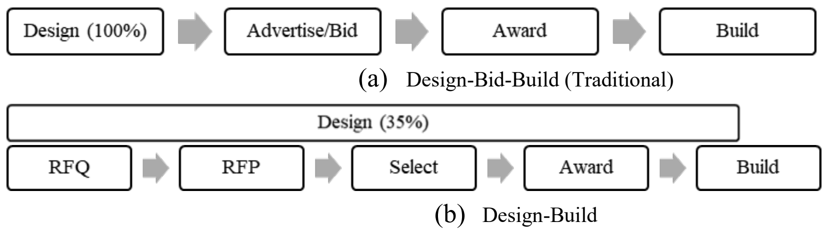

Figure 1. Project Delivery Sequences of Traditional (a) and DB (b) Delivery Methods

Fixed budget-best value, also known as "design-to-costs", allows state DOTs to generate the greatest amount of work while achieving the best value for dollars expended (FHWA 2013). This approach encourages the proposers to submit the proposals with the best value while staying within the defined budget. As a variation of best value procurement methods, a FB-BV approach provides state DOTs a choice for selecting evaluation and selection criteria, such as project scope, qualifications, and schedule that meet or exceed their project requirements. The FB-BV algorithm includes the two major components, technical score and project price (i.e., $Algorithm\text{: } Award\ T_{max}, Fixed\ P$). With these two factors, the state DOT selects the proposal that obtains the maximum technical score while fulfilling the premise of the fixed budget. The technical score can be calculated based on several types of parameters (e.g., time, qualifications, and design) that the owner requires for the project goal. As the FB-BV evaluates the proposal by using project scope, qualifications, schedule, and non-cost factors (Scott et al. 2006). Figure 2 depicts the best-value procurement process. For the FB-BV, the budget constraints should be incorporated in the first step, where the agency screens the candidate project and define the project goals/benefits. As many highway construction projects have suffered from significant cost overruns, this approach provides an attractive alternative for procuring a project with a tight budget.

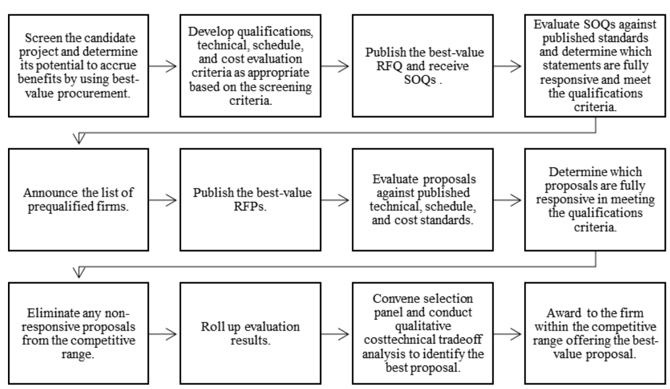

Figure 2. Flow Chart of Best-Value Procurement Process (Scott et al. 2006)

The FB-BV approach maximizes improvements within the defined budget and provides incentives to proposers to utilize the full budget. This approach increases competition and exploits the budget as much as possible, which can result in maximum improvements for the project. The FB-BV has several advantages and disadvantages. The major advantage of this approach is that it can be a good tool for controlling costs and keeping a project within budget. However, the agencies may get less work done than originally planned if the budget is too tight. In addition, this approach may require more time for evaluating the proposal and have challenges in selecting the contractor if selection criteria are not clearly defined and defendable (Scott et al. 2006; WSDOT 2013). Although the literature has shown that the FB-BV is an effective method for maximizing the value of dollars of projects, few have provided the current state of practices of a FB-BV contracting strategy. Therefore, the objective of this study is to identify and analyze FB-BV practices in state DOTs. This study contributes to the state of knowledge and practice by examining the literature and practice of the FB-BV procurement method, which provide an effective strategy to deliver projects under a strict budget.

Research Methodology

The primary goal of this study is to analyze the FB-BV practices and explain recommendations for enhancing the process of delivering highway projects. To achieve this goal, this study conducted a critical scanning process on the FHWA and state DOTs' websites to determine their execution process and interviews with several state DOTs to identify successful case studies related to a FB-BV contracting strategy. This study presents FB-BV procurement practices and case studies from four state highway agencies in the United States including, Idaho, Michigan, Utah, and Colorado. Table 1 provides the summary of state DOTs' FB-BV contracting strategies and case studies.

Table 1

Summary of State DOTs' FB-BV Contracting Strategies and Case Studies

DOTs	FB-BV Procurement Process	Case Studies
Idaho	Pass/Fail and Scored Criteria (e.g., formatting, executive summary, legal, financial aspects of proposals, organizational structure, project management, maintenance of traffic, and project-specific technical and quality factors)	Bridge deck preservation in 2010 Resurfacing in 2015 Seal coating projects in 2016
Michigan	Three Types of Projects for the FB-BV approach (i.e., Type 1: projects receive bids by the units of work that can be completed for a State fixed price, Type 2: projects receive bids by the units of work that can be completed for a maximum price, and Type 3: projects receive bids through a traditional low-bid process)	Crack sealing work in Hillsdale, Ingham, Jackson, and Lenawee counties in 2012
Utah	The relative significance of UDOT (i.e., High, Medium, and Low)	I-15 Corridor Expansion project in 2008
Colorado	Adjectival rating for each evaluator category	Transportation-Expansion project in 1999

Results and Discussions

Under the provisions of Special Experimental Project No. 14 (SEP 14) (FHWA 2016), several state departments of transportation currently utilize the FB-BV approach to maximize the use of their available funds. To document the state of practice of a FB-BV contracting strategy, a comprehensive review of academic and professional literature was conducted. In addition, a critical scanning process was conducted on the FHWA and state DOTs websites to determine their execution process and case studies related to a FB-BV contracting strategy. The results of scanning indicate that the use of a FB-BV approach was successfully utilized in several state DOTs, including Idaho, Michigan, Utah, and Colorado DOTs.

Utah Department of Transportation (UDOT)

The Utah department of transportation (UDOT) defines the FB-BV, also called fixed price-best value, in the context of three objectives, including knowing funding limitations, maximizing scope for the price, and encouraging innovation (UDOT 2016). With this procurement method, UDOT aims to maximize the amount of work under a single contract while spending all authorized funding for the contract. Besides, UDOT encourages the proposers to develop innovative solutions to achieve the state's goal (UDOT 2013). Since the FB-BV approach provides higher flexibility in design and construction methods and techniques than that in traditional procurement methods, such as low bid, UDOT utilizes this method in DB projects. The selection process of the FB-BV follows a similar process of best value DB procurement (UDOT 2016). First, UDOT develops and approves project goals. In this step, the process begins with an understanding of the major factors impacting the project based on environmental study information or other known issues. The project team and region leadership should clearly define the project goals based on scope, schedule, budget, and impacts on the public. Based on the project goals, the project team and region leadership apply relative weights to goals and develop evaluation criteria for each scored goal. The project goals and evaluation criteria should be refined by the selection committee throughout project development. Finally, the project team and region leadership request approval of the project goals and evaluation criteria from the selection committee.

Next, UDOT receives and evaluates proposals. Once the project goals and evaluation criteria are approved by the selection committee, the proposals will be received and evaluated by the committee. There are three types of committees involved in the evaluation process. The analysis committee identifies the added values, risks, strengths, and weaknesses of proposers. The evaluation committee offers one-one meetings with each proposer. Lastly, the selection committee meets with the evaluation committee early in the process to discuss the project and agrees on the purpose and objective of the project. Next, through the review of blinded technical and blinded price proposals, the selection committee determines the overall best value selection and provides a written and blinded justification of the best value selection. To measure the quantitative and qualitative benefits of proposals, UDOT uses evaluation adjectives, including "HIGH", "MEDIUM", and "LOW", which indicate the relative significance of UDOT. An example of evaluation factors for project definition is shown in Table 2.

Table 2

Example of Evaluation Factors and Category

Evaluation Factor	Evaluation Category
HIGH	The number of I-15 lane and shoulder miles added or improved, by type and level of improvement. The number of interchanges reconstructed or improved and the level of improvement. Operational metrics of mainline, at and between interchanges. Operational metrics of mainline transitions to existing facilities. Level of improvement to regional mobility associated with mainline improvements using the results from the transportation demand management
MEDIUM	Level of improvement of the interchange operations using the results from the traffic engineering models Other operational improvements include the number and nature of decision points, length of weave areas, width and location of shoulders and refuge areas, etc. Number of intersections improved and the level of improvement
LOW	For areas between American Fork Main Street and Provo Center Street Operational metrics in cross-street transitions to existing facilities Extent and functionality of non-motorized improvements

An Example of Fixed Budget-Best Value from UDOT

The first FB-BV project in UDOT was the 24-mile I-15 Corridor Expansion (I-15 CORE) project in 2008. The major challenge of this project was the budget cut from \$2.6 billion to \$1.7 billion. Using a FB-BV approach and proactive risk management, UDOT was able to deliver all the basic configuration scope with additional elements while spending \$1.1 billion which was less than the state legislature-approved budget. The I-15 CORE project is an exceptionally successful example of a FB-BV procurement method. All proposers submitted more scope with innovative solutions for design and construction and did not exceed the approved budget. The winning proposal provided the fastest schedule, more lane miles, fewer lane closers, and an additional inch of pavement that has a longer life and lower life cycle costs (UDOT 2013; WSDOT 2013). The evaluation criteria for I-15 CORE include technical, must-have requirements, pass/fail elements, and project goals and values. the scores for three categories include 60% project definition, 20% maintenance of traffic, and 20% schedule. Overall, UDOT verified that a FB-BV approach is an effective contracting strategy in maximizing the amount of work while staying within the approved budget.

Colorado Department of Transportation (CDOT)

The Colorado Department of Transportation (CDOT) also utilized a FB-BV, also called, the fixed price-best proposal procurement method, when the agency has a budget constraint and wants to maximize the scope of work. This method provides proposers with flexibility in selecting the technical approach and scope for a project within the defined budget. In addition to the basic configurations, CDOT usually defines additional scope elements, known as "Additional Requested Elements (AREs), so that proposers can have options to select. As more AREs are included in proposals while staying within the budget, the proposers will obtain a higher evaluation score. To achieve the project goal, the agency should carefully define the budget and the AREs for a project. The selection process for a FB-BV approach is completed with two steps (CDOT 2016). First, CDOT develops the evaluation procedure. The process begins with determining the project goals. CDOT determines the project goals by using best-value parameters including cost, time, scope, technical design consideration, and construction operation consideration (such as Maintenance of Traffic (MOT) and Public Involvement parameters). The best value scoring parameters are shown in Table 3:

Table 3

Relating Project Goals and Values to Best Value Scoring Parameters

Project Goals	Possible Best Value Parameters
Maximize operational capacity	Project technical approach and commitments & AREs
Maximize use of available funds	AREs & Additional proposal scope commitments
Manage impacts during construction, minimize inconvenience to the traveling public, or minimize inconvenience to the stakeholders	MOT approach and commitments PI approach and commitments, Time of completion, & Duration of construction impacts
Complete the project on or before a set date	Time of completion & Time to obtain key schedule milestones
Provide a high-quality project	Quality management plan approach and commitments & Technical approach and commitments
Safety of the public and workers	Safety management plan approach and commitments
Maximize project durability or	Maintenance level of service commitments
Minimize life cycle costs of a project	Low-maintenance structures, Low-maintenance pavement, & Other low-maintenance designs

Next, CDOT receives and evaluates proposals with evaluators. Each evaluator reviews and assesses individual SOQs/Proposals using the overall criteria set and records observations using provided evaluation forms. Each evaluator determines an adjectival rating for each evaluator category using the adjectival evaluation and scoring guide as shown in Table 4. Each evaluator uses a best-value evaluation formula to determine the total score. Each parameter is then assigned specific scoring criteria. The maximum total proposal score is 100 points. Table 5 shows Alternative Algorithms to calculate the total score. Moreover, the evaluation committee and technical advisors meet and discuss the submitted SOQs/Proposals and the evaluation forms. The evaluation committee then determines the final score for each proposal. Lastly, CDOT provides the opportunity for one-one meetings for each proposer that requests a meeting within the allowed time.

Table 4

Adjectival Evaluation and Scoring Guide

Adjective	Description	Percentage of Max. Score
Excellent	SOQ/Proposal supports an extremely strong expectation of successful project performance if ultimately selected as the contractor. SOQ indicates significant strengths and/or some minor strengths and no weaknesses. The submitter provides a consistently outstanding level of quality.	90-100%
Very Good	SOQ/Proposal indicates significant strengths and/or some minor strengths and no significant weaknesses. Minor weaknesses are offset by strengths. There exists a small possibility that, if ultimately selected as the contractor, the minor weaknesses could slightly adversely affect successful project performance.	75-89%
Good	SOQ/Proposal indicates significant strengths and/or some minor strengths. Minor and significant weaknesses exist that could detract from strengths. While the weaknesses could be improved, minimized, or corrected, it is possible that if ultimately selected as the contractor, the weaknesses could adversely affect successful project performance.	51-74%
Fair	SOQ/Proposal indicates weaknesses, significant and minor, which are not offset by significant strengths. No significant strengths and few minor strengths exist. It is probable that if ultimately selected as the contractor, the weaknesses would adversely affect successful project performance.	25-50%
Poor	SOQ/Proposal indicates the existence of significant weaknesses and/or minor weaknesses and no strengths. SOQ indicates a strong expectation that successful performance could not be achieved if ultimately selected as the contractor.	0-24%

Table 5

CDOT Design-Build Alternative Algorithms to Determine Total Evaluation Score

Alternative Algorithm	Formula	Result
Technical Score Adjusted by Price	Total Score = Ts x (GMP/Pp)	The highest score determines the apparent best value.
Proposal Price Score Adjusted by Technical Score	Total Score = Pp/Ts	The lowest score determines the apparent best value.
Qualitative Technical Score + Quantitative Price Score	Total Score = Ts + (Pmax x Plow/Pp)	The highest score determines the apparent best value.
Qualitative Technical Score + Quantitative Price Score (based on defined dollars per point)	Total Score = Ts + [Pmax – ((Pp – Plow)/($ per Pt))]	The highest score determines the apparent best value.

Note: Ts = Technical Proposal score: the sum of all other best value scoring elements, including AREs; Pmax = Maximum Proposal price points; Pp = Proposal price; Plow = Lowest Proposal price; $ Per Pt Factor = A defined dollar amount per point value; GMP = Guaranteed Maximum Price

An Example of Fixed Budget-Best Value from CDOT

CDOT utilized a FB-BV approach in the $1.67 billion Transportation-Expansion (T-REX) DB project in 1999. The scope of this project is to add 19 miles of double-track light rail, build 13 stations with park-n-Rides, add 13 light rain vehicles to the Regional Transportation District (RTD)'s fleet, and construct a new light rail maintenance facility in Englewood. The project goals of this project are to minimize inconvenience to the public, meet or beat the total program budget of $1.67 billion, provide a quality project, and meet or beat the schedule to be fully operational by June 30, 2008 (CDOT 2003). CDOT achieved significant schedule and cost savings because of the innovative funding and DB/FB-BV approach. The winning proposal was selected based on a best-value evaluation process by looking at technical and price proposals. The Innovative contracting strategy enabled CDOT to complete the project within schedule and under the approved budget.

Idaho Transportation Department (ITD)

The Idaho Transportation Department (ITD) also started to experiment with a FB-BV, also called the fixed Price-best design approach, under the provisions of SEP 14. ITD uses this contracting strategy in a DB delivery method to yield a greater amount of work than the low-bid method and not an additional element of work. Thus, ITD selects a proposer who submits the maximum scope or quantity of work within the approved budget. The selection process of the ITD's FB-BV approach includes the development of an evaluation procedure and evaluation of proposals (ITD 2014). For instance, the process begins with defining the project goals for the project. Next, the project team needs to develop the project scope, estimated cost, and maximum time allowed for the project. Based on the project goals and other information, the evaluation criteria and process need to be developed. Next, proposers submit technical and price proposals concurrently. ITD should keep price proposals confidential until technical proposals have been evaluated, scored, and reviewed by higher levels. First, the evaluation committee will evaluate technical and price proposals by using pass/fail and score criteria. Pass/fail criteria include formatting, executive summary, legal, and financial aspects of proposals, as well as participant experience. Next, score criteria consist of organizational structure, project management, maintenance of traffic, and project-specific technical and quality factors (i.e., design and construction qualifications, innovation, design and construction quality, and time of completion). Besides, the selection committee discusses and reviews the evaluation techniques and price proposal with the evaluation committee and documents the results of the evaluation. Lastly, the contracting officer approves the evaluation of the technical and price proposal and summary of scores and feedback from evaluators.

Examples of Fixed Budget-Best Value from ITD

ITD tried FB-BV with several project types (i.e., bridge deck preservation, resurfacing, and seal coating projects). Table 6 provides examples of project types in the state of Idaho that the FB-BV procurement method has been utilized. For example, in 2010, ITD used FB-BV in a bridge deck preservation project. ITD required the bidders to determine the total number of square yards of deck preservation that they could accomplish for the fixed budget of $700,000. ITD selected the bidder who submitted a bid with the largest square yardage of 27,641 squad yards. In 2015, ITD had a fixed budget of $651,500 for the roadway resurfacing projects between MP36.783 and MP48.869 in Idaho. The contractors were required to bid a tonnage of the crushed aggregate base that is excavated or blasted from the source, crushed, placed, and compacted. The range of the tonnage was between 14,115 and 41,448 tons. ITD procured the contract to the bidder who submitted the biggest tonnage, 41,448 tons. In 2016, ITD also used the FB-BV approach for seal coating projects in District 4 of the state of Idaho. The bidders bid how many square yards they could seal coat for the fixed budget of $2,948,000. The range of the square yards is between 1,433,897 and 1,616,228.07 square yards. The winning bid was the bidder who submitted the bid with 1,616,228.07 square yards. Using a FB-BV, ITD achieves equal to or better than the base concept.

Table 6

Example of Fixed Budget-Best Value Projects in the State of Idaho

Construction Year	Budget	Work Type	Winning Bid
2010	$7000,000	Bridge Deck Preservation	The largest square yardage (27,641 sq. yd.)
2015	$651,500	Roadway Resurfacing	the biggest tonnage (41,448 tons)
2016	$2,948,000	Sealcoating	The largest square yardage (1,616,228.07 sq. yd.)

Michigan Department of Transportation (MDOT)

The Michigan Department of Transportation (MDOT) uses a FB-BV, also called fixed price-variable scope, to maximize the amount of work within a maximum budget. Thus, the contractor providing the most scope/work for the established budget is awarded the contract. MDOT classifies projects into three types that can be procured by a FB-BV approach (MDOT 2015). In Type 1 projects, MDOT receives bids by the units of work that can be completed for a fixed price. The selected contractor is the bidder that proposed the most units of work for the given fixed price. Type 1 has been used for HMA crack seal, chip seal, and fog seal projects, bid by the lane mile. Next, in Type 2 projects, bids are received by the units of work that can be completed for a maximum price. Contractors bid units of work and may also bid a price for that work that is below the maximum price. The selected contractor is first determined by the bidder that proposes the most units of work, for their determined maximum price. If two or more contractors propose the same amount of work, then the successful bidder is determined by which of those contractors proposed the lowest maximum price. Type 2 has been used for bridge deck epoxy overlay work, bid by the square yard. Lastly, for Type 3 projects, bids are received through a traditional low-bid process. The contractor provides unit prices for pay items provided in the schedule of items. The selected contractor is determined by the lowest submitted bid. The project is awarded at a low bid price. With Type 1, the proposal submits the maximum amount of work while spending all authorized funding. On the other hand, the Type 2 projects allow MDOT and proposers to adjust the maximum price depending on the maximum amount of work submitted by proposals. The Type 3 project will go through the normal low-bid process. It allows additional work until final construction costs are equal to the engineer's estimate (Youngs 2013).

MDOT considers a combination of technical and price factors to select the winning bid in a FB-BV approach. The selection process for a FB-BV method also includes two steps. First, MDOT develops and approves project goals. In this process, the project manager prepares a proposal evaluation plan that details the process and criteria to be used during technical proposal evaluation. The selection team develops scoring criteria for the technical portion of the evaluation. Next, MDOT receives and evaluates proposals. In this step, the proposals will be reviewed by a selection team consisting of the project manager, staff from the region/transportation service center, the innovative contracting unit, the central selection review team (CSRT), as well as other technical experts. The project manager and deputy project manager review the technical proposals by using the pass/fail criteria in the RFP and score the proposals. The project manager provides the selection team with the submitted proposals and the results of the technical proposal review. Next, the selection team reviews the technical proposal and determines the score for each proposal with justification. Lastly, the project manager provides CSRT with the information for final review and approval. The results will be posted after approving the scores.

Examples of Fixed Budget-Best Value from MDOT

MDOT also utilized the FB-BV contracting strategy in several projects to achieve the maximum amount of work within the fixed budget for the project. In 2012, MDOT used this innovative approach for crack sealing work in Hillsdale, Ingham, Jackson, and Lenawee counties in the state of Michigan. The scope of this project included a maximum of 103.78 miles of hot mix asphalt crack treatment and overband crack filling on 15 segments of various roadways in Michigan. Three bidders submitted the bids with the maximum number of roadbed miles of work that could be completed for the established project budget of $387,000. To evaluate proposals, MDOT had two evaluation criteria: past performance and maximum amount of work. MDOT awarded the contract to the bidder who submitted the maximum length of 74.43 roadbed miles, which is longer than the Department's estimate of 70.62 miles (MDOT 2012).

Conclusions

State DOTs experience crucial funding limitations for delivering much-needed construction and rehabilitation projects that are necessary for maintaining the quality of transportation infrastructure systems. Innovative contracting strategies, such as a fixed budget-best value procurement method, can help state DOTs complete a project within an established budget. This paper reviewed the current state of practices in the FB-BV procurement method and identified best practices in the utilization of this innovative contracting method.

This study provided important implications of the findings for implementing a FB-BV procurement method in the delivery of successful highway projects. First, it is important to define project goals/benefits based on scope, schedule, budget, and public interest in implementing the FB-BV procurement method. Next, establishing rigorous evaluation criteria (e.g., cost, time, and design alternatives) and the weights for the criteria to evaluate the proposals based on the project goals is critical to selecting the best proposer for a project while allowing higher flexibility in proposing design and construction solutions. Moreover, including committees for refining project goals, establishing evaluation criteria, and reviewing/selecting the proposals is essential for implementing the FB-BV procurement process and increasing transparency of the contract award. Lastly, this study found that defining the basic configuration scope and allowing the proposers to include the maximum amount of work or additional scope elements in their proposals while staying within the fixed budget are critical to achieving the best values of a project.

Therefore, the findings of this study contribute to the state of knowledge and practice of the FB-BV procurement method and help state DOTs establish an effective process for implementing the FB-BV contracting method under a strict budget.

References

CDOT. (2003). "TREX Fact Book 2003", Colorado Department of Transportation.

CDOT. (2016). "Design-Build Manual". Colorado Department of Transportation, Denver, Co.

FHWA. (2013). "Programmatic Use of Fixed Price Variable Scope Contracting on Capital Preventative Maintenance Projects", Federal Highway Administration.

FHWA. (2016). "SEP-14 Active Project List", Federal Highway Administration.

ITD. (2014). "Alternative Project Delivery." Idaho Transportation Department.

MDOT. (2012). "Final Evaluation Report Special Experimental Project 14 (SEP-14): Fixed Price Variable Scope Contracting", Michigan Department of Transportation.

MDOT. (2015). "Innovative Construction Contracting Guide", Michigan Department of Transportation.

Scott, S., Molenaar, K. R., Gransberg, D. D., and Smith, N. C. (2006). "Best-Value Procurement Methods for Highway Construction Projects", National Cooperative Highway Research Program, Washington, D.C.

UDOT. (2013). "OTEC – Financing Our Future Roles and Responsibilities on DB Contracts", Utah Department of Transportation.

UDOT. (2016). "Best Value Design-Build Selection", Utah Department of Transportation.

WSDOT. (2013). "Appendix N: Design-Build Delivery White Papers", Washington Department of Transportation.

Youngs, C. (2013). "Innovative Contracting", Asphalt Pavement Association of Michigan 2013 Annual Conference.

Dear Editor,

We would like to thank the editor and reviewers for their helpful and constructive comments and suggestions. Careful and serious attention has been given to addressing all the comments.

Dear Reviewer 1,

Thank you very much for your great comments.

Comments: This paper explains the fixed-budget best-value procurement process with case studies. The authors just explained basic general procurement steps, which do not significantly add to the body of knowledge to accept this paper for publication. The reviewer encourages authors to present critical findings that add to the body of knowledge.

Responses: we revised the conclusions to include the major findings of this study and included the following sentences.

This study provided important implications of the findings for implementing a FB-BV procurement method in the delivery of successful highway projects. First, it is important to define project goals/benefits based on scope, schedule, budget, and public interest in implementing the FB-BV procurement method. Next, establishing rigorous evaluation criteria (e.g., cost, time, and design alternatives) and the weights for the criteria to evaluate the proposals based on the project goals is critical to selecting the best proposer for a project while allowing higher flexibility in proposing design and construction solutions. Moreover, including committees for refining project goals, establishing evaluation criteria, and reviewing/selecting the proposals is essential for implementing the FB-BV procurement process and increasing transparency of the contract award. Lastly, this study found that defining the basic configuration scope and allowing the proposers to include the maximum amount of work or additional scope elements in their proposals while staying within the fixed budget are critical to achieving the best values of a project.

Therefore, the findings of this study contribute to the state of knowledge and practice of the FB-BV procurement method and help state DOTs establish an effective process for implementing the FB-BV contracting method under a strict budget.

Dear Reviewer 2,

Thank you very much for your great comments.

Comments: 2nd level headings incorrect

Responses: Per your comments, we checked the format of 2nd-level headings and other formats and changed the 2nd-level headings.

Comments: There are less than ten mistakes with formatting, such as capitalizing titles or agencies (p. 3 has several).

Responses: Thank you. We fixed the mistakes related to capitalizing titles, agencies, and personnel throughout the paper.

Comments: A visual would benefit this study, to illustrate the FB-FV process, such as a decision tree or comparison model to the alternative/traditional procurement method.

Responses: Thank you for your suggestions. We added two figures (Figure 1 and Figure 2) to illustrate the alternative and traditional delivery methods and the FB-BV procurement process in the paper.

Generation Z's Learning Experience in Engineering Classroom: Qualitative Study of Lack of Critical Thinking in the Classroom Activities

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With the influx of a new workforce (Generation Z) into the construction industry and their dominance in higher education, whether the current educational experience is suitable for this new cohort has been investigated focusing on terminal applications such as IT applications (VR) and software usages (Revit). Limited attention is given to the cognitive process of learning of Generation Z despite their different knowledge acquisition practices – learning is to learn "where to find information" rather than analyzing and synthesizing information. This study did qualitative research and identified driving factors using the Girvan Newman algorithm. From the community analysis, the study found that seeking assistance coupled with the lack of construction fundamentals and limited understanding of construction project documents does not help improve learning. The right interpretation of the problem statement and enough understanding of the process are required for the successful execution of activities in the project, which can be obtained through the preparation of basic knowledge such as plan reading and construction fundamentals. In addition, providing opportunities for self-assessment through metacognition questions should be counted in to promote active learning and exercising critical thinking skills that are analyzing arguments, inferencing, judging information, and making decisions.

Key Words: Construction Education, Graph Theory, Girvan Newman Algorithm, Critical Thinking, Qualitative Research

Introduction

In the prior study assessing the Generation Z students' learnings through the investigation of quantitative data from students' works, observations suggested that Generation Z students showed limited critical thinking skills (An & Ryoo, in review). Misinterpretation of problem statements, identifying wrong inputs due to misjudgment, and blindly following and applying the value from calculations without thinking about industry common senses were the main issues identified, and they are comparable to what Lai (2011) defined as components of critical thinking skills: analyzing arguments, making inferences, making judgments, and making a decision or solving problems. Holding the qualitative approach, this study investigated the driving factors of the limited critical thinking skills of today's students.

Grand changes in the industry have been predicted with the mass retirement of baby boomers and the influx of a new generation equipped with digital gear (Flood, 2020). In addition to the expected workforce changes, the outbreak of the worldwide pandemic resulted in increased flexibility in workplace practices (Prager, Rhoads, & Martínez, 2022). This flexibility of workplace practices affected teaching and learning in higher education institutions. Emergency remote teaching was executed during the pandemic (Masuku, 2021). The students who were heavily affected by this abrupt change and who will occupy the industry soon are Generation Z.

Efforts have been made to understand and to support a cohort of students called Generation Z. Generation Z is expected to be the dominant workforce in the 2020s and is currently in college (Seemiller & Grace, 2016). Rothman (2016) argued that instructors teaching this generation should be prepared to incorporate Information Technology (IT) in their classrooms such as software, hardware, and even social media. Revit (BIM), Navisworks, and Primavera 6 or Microsoft Project are common examples in today's classroom in construction education, and incorporating VR or MR is in its experimental stage (Vasilevski & Birt, 2020). Even a virtual construction field trip was attempted in place of actual field trips to the construction site (Dada, Seifan, & Berenjian, 2020).

Generation Z is known to be deviant from the previous generation, and their discrepant characteristics are attributed to the environment they grow up. The year in which Generation Z began to be born was also incidentally the year in which the term, the Internet was awarded its definition by the Federal Networking Council (Leiner et al., 2009). Thereafter, the Internet became the preferred medium of information (Coelho, 1998). Generation Z is said to be connected to the network all the time placing any information a click away through smartphones on the road, broadband Internet access at home, and online connection at school (Francis & Hoefel, 2018; Seemiller & Grace, 2017).

The Generation Z cohort is said that they are visual learners. With a more developed area in the brain part responsible for visual ability (Rothman, 2016), they are found to learn by observing (Seemiller & Grace, 2017), which has its basis in their affinity to learn from watching videos mainly on YouTube. Rothman (2016) found that the Generation Z cohort has a limited span of attention, and he finds its cause in the Internet usage. Being accustomed to being bombarded with constant changes every several seconds from social media, they switch from one task to another rather than focusing for a long time (Rothman, 2016).

Research has been done to accommodate and serve better this Generation. A study to learn the current campus environment focusing on digital or network connection (Seemiller & Grace, 2017) and an investigation on teaching and learning materials to meet the preference for visual learning materials (Clarke III, Flaherty, & Yankey, 2006) are good examples. As such, researchers pay more attention to incorporating technology into the classroom. Little attention has been given to the cognitive process of Generation Z students' learning although their way of information acquisition is known to be non-identical to the previous learners; they learn to know "where to find information about" (Ivanova, 2009, p.IV.2-1) rather than undergoing the process of critical thinking: analyzing and synthesizing new information (Dede, 2005). This study investigated the driving factors that impact Generation Z students' learning in terms of cognitive processes in higher education institutes so that it examines possible solutions that support today's students to have better educational experiences.

Literature Review

Today's students in higher education – Generation Z

Generation Z is those who were born between 1995 and 2012 (Andheska, Suparno, Dawud, & Suyitno, 2020; Chicca & Shellenbarger, 2018; Francis & Hoefel, 2018; Seemiller & Grace, 2019). Each generation (e.g., Veterans and Baby Boomers) grew up in different conditions and has different styles and expectations of learning (Rothman, 2016). When talking about styles and expectations of learning in Generation Z, the influence of the Internet is undeniable. Seemiller & Grace (2016) found that growing up in a world shaped by the Internet, Generation Z students come to class digitally connected, so reference materials are just a click away, and YouTube videos can supplement their academic classes; online search gives answers in a few seconds whether the answers are right or wrong. According to Rothman (2016), due to the external environment (information technology advances), the brains of Generation Z have become wired to visual imagery, so they have far more developed brain parts responsible for visual abilities, and this trait makes them visual learners, or at least they have a preference on visual materials.

According to Cilliers (2017), they use PC recordings instead of note takings opting for electronic learning materials for record keeping, raise questions online using Learning Management System (LMS) even in face-to-face course administrations, and demand instant information and communications rather than waiting for a response. However, in contrast to online (remote) communication preference, Generation Z students prefer more contact (synchronous) sessions and lectures. Then, does the current campus provide enough support for the current students? Seemiller & Grace (2016), former student affairs professionals, studied Generation Z students to learn the styles, motivations, and perspectives of Generation Z students, and they concluded that the current campus environment does not meet the needs, the interests, and the learning preferences of Generation Z students.

Rothman (2016) also suggested that Generation Z suffers from the inability to focus and analyze complex information or issues due to "Acquired Attention Deficit Disorder (AADD)," which is developed by information technology advance. The brain expects short and rapid bursts of information due to a bombardment of small bits of information from being connected to the virtual world such as YouTube, Twitter, and Facebook. This trait casts doubt on whether they could reflect their learnings, one component of critical thinking.

Critical Thinking & Metacognition

Jackson (2020) suggested that decision-making and problem-solving are the most critical skills that should be trained for construction managers, and he also asserted that "the solutions to many construction issues cannot be found in a book or relayed in a seminar - they are discovered by using critical and creative thinking skills" (p. 59). Bloom's taxonomy hierarchically presents information processing skills with "comprehension" at the bottom and "evaluation" at the top, and the three highest (analysis, synthesis, and evaluation) represent critical thinking skills (Kennedy, Fisher, & Ennis, 1991). Lai (2011) defined what to include in critical thinking skills; Lai argues that analyzing arguments, making inferences, making judgments, and making decisions or solving problems are abilities that should be included. Mathiasen & Andersen (2020) defined critical thinking as reasonable, reflective thinking focusing on the given tasks.

Metacognition is defined as "awareness or analysis of one's own learning or thinking process" (Merriam-Webster), and more metacognitive awareness is found among high-achieving students (Hartman, 2001). Incorporating metacognitive tools was effective even in Generation Z students (Caratozzolo & Á, 2018). Tanner (2012) showed the possibility of overall academic success when having metacognition questions on their learning.

Qualitative Research

Qualitative research is an interpretive activity of the population (Denzin & Lincoln, 2011) and gives an in-depth understanding of reality (Kuckartz & Kuckartz, 2002). Interviews, observations, and documents are the data source of qualitative research (Patton, 2005). How many data sets are required for data saturation has been an issue, and Guest, Bunce, & Johnson (2006) experimented to learn how many interviews are enough for quality research and showed that data saturation was reached in 12 interviews, and the meta-theme presented with 6 interviews regarding non-probabilistic, purposive sample sizes.

The generalizability of research outcomes is another issue in qualitative research (Smith, 2018), and the use of a software tool has arisen as a powerful complement (Kuckartz & Kuckartz, 2002). Multiple tools exist, among which MAXQDA is a more reliable tool (Wolff, 2021). MAXQDA covers not only qualitative data but also quantitative data in mixed methods data analysis (Marjaei, Yazdi, & Chandrashekara, 2019). MAXQDA allows even a systematic analysis of qualitative data increasing research reliability (Rädiker & Kuckartz, 2020).

MAXQDA can do content analysis and thematic analysis (Kuckartz & Kuckartz, 2002; Marjaei et al., 2019). According to Marjaei et al. (2019), by interpreting and coding textual material and evaluating texts by counting words and phrases, the research can convert qualitative data to quantitative data using MAXQDA; in addition, through the relationship between the sentences and phrases, thematic analysis can be performed. In combination with MAXQDA, UCINET is a software to analyze social network data, and it comes with NetDraw, a visualization tool (Borgatti, Everett, & Freeman, 2002).

The Girvan Newman algorithm, an algorithm of Graph theory which is to construct communities from networks, in UCINET constructs communities/clusters by removing edges from the original network; the betweenness of all edges in the network is calculated, and the edge with the highest betweenness is removed. Until no edges remain, calculating betweenness and removing edges is repeated. After removing edges – when communities/clusters were detected, the Girvan Newman algorithm calculates the modularity (Q value) of the graph; a higher value suggests a more significant community structure, and in most cases of successful community detection, Q is between 0.3 and 0.7 (Despalatović, Vojković, & Vukičević, 2014). Betweenness is defined as the number of shortest paths between pairs of vertices. The betweenness centrality is a measure of the influence of a node over the flow of information, leading factors of communities (Girvan & Newman, 2002).

Methodology

As illustrated in Figure 1, this qualitative research consisted of three parts: (1) interviewees' experience in problem-solving in a construction project control, (2) data collection through interviews, and (3) data analysis. A purposeful sampling was adopted to recruit the interviewees that represent the class. Students in the Construction Estimating course in FA 2022 were pre-defined into three ranges according to the points in Exam I, and four students from each point range were invited; 12 students in total were invited to achieve data saturation, but only 6 students accepted reaching the meta-theme.

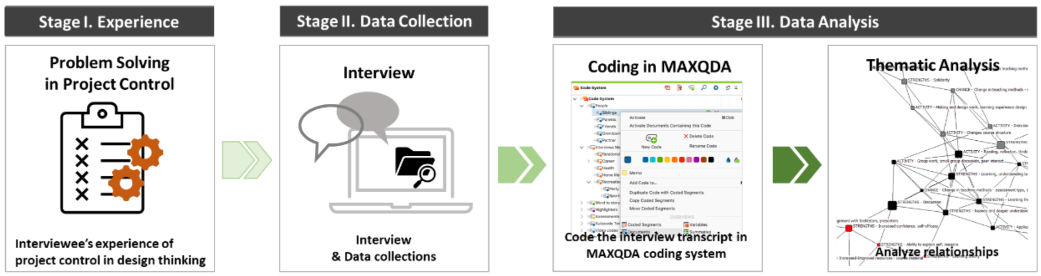

Figure 1. Study Workflow of Interview Analysis

We did each interview through a video conferencing application (Zoom) so that the interview transcript was automatically obtained by using the embedded speech-to-text function in Zoom. The interview transcript was processed to make it sound reasonable before being fed into MAXQDA. Once fed into MAXQDA, the transcript was coded in the MAXQDA coding system. Applying the statistical tools embedded in MAXQDA to the coded data, the qualitative data was converted into a quantitative one, which was mapped for thematic analysis (relationship analysis) and from which a diagram was generated. UCINET was used to map the coded data. The Girvan Newman algorithm in UCINET was used to identify communities, and betweenness centrality was calculated, through which the factor(s) with considerable influence within a community were identified.

Result

Three communities were identified, whose modularity (Q value) is 0.488 indicating that the communities are significant enough. As shown in Figure .2, the three communities have differences. Students in the black community have a limited understanding of the activity goal. Although they have a reasonable understanding of documents like drawings and specifications of the given project, they tend to be dependent on instructors in their learning; their learning materials are mostly from instructors (lecture and lecture notes). It is reasonable to suggest that they have a limited affinity to active learning. The value of betweenness centrality in Figure 3 indicates that *"Whole Understanding-Dependent on the instructor"* and (2) *"Activity Goal-Limited understanding"* are leading factors in this community.

The blue community in Figure 2 indicates an assistance-seeking characteristic. The learning materials are different from that of assistance. They use instructor-provided learning materials such as textbooks, In-Class-Exercises (ICE), and homework, but they google for quick information search. Students in this community understand problem statements, but they have a limited understanding of the process, which suggests that they lack discipline-specific fundamentals. They also seek extra assistance from peers to overcome difficulties. The highest betweenness centrality of "*Whole Understanding-Understand prob statement not process*" in Figure 3 confirmed that improving the understanding of how to solve the given problem (process) through expanding their learnings to include materials other than ICE and homework is required.

Students classified in the red community in Figure 2 defined the goal of the activity wrong. They are independent learners; they seek online assistance (online search and tutoring); to overcome learning obstacles, they spend time on tasks, but all limited understanding of drawings and specifications, limited fundamentals, and poor problem statement understanding combined attribute to a low level of learning – too general or too direct for thorough understanding on process. Self-learning approaches (high betweenness centrality for *"Obstacles – Overcoming strategies-spending time, experience"* and *"Assistance – Online search and tutorials"* in Figure 3) in isolation with ways that confirm whether their learning is on the right way is discouraged according to findings in red communities.

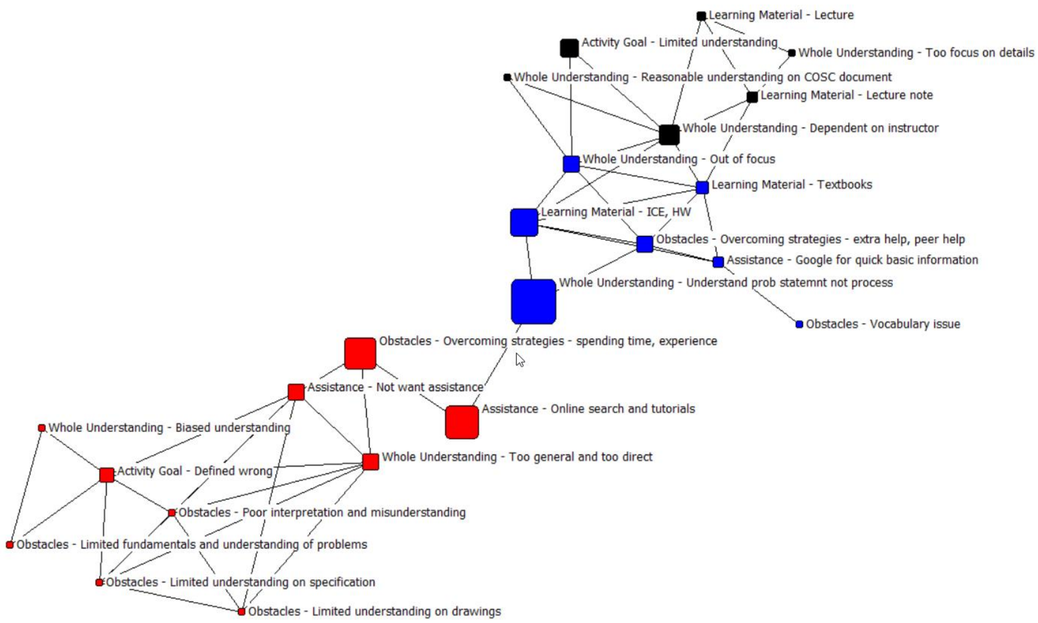

Figure 2. Communities Identified Using the Girvan Newman Algorithm in MAXQDA and UCINET

The distance between nodes is not scaled. The different color represents different communities/clusters. The different sizes of nodes represent the difference in betweenness centrality; the bigger the nodes are, the higher the value of betweenness centrality is.

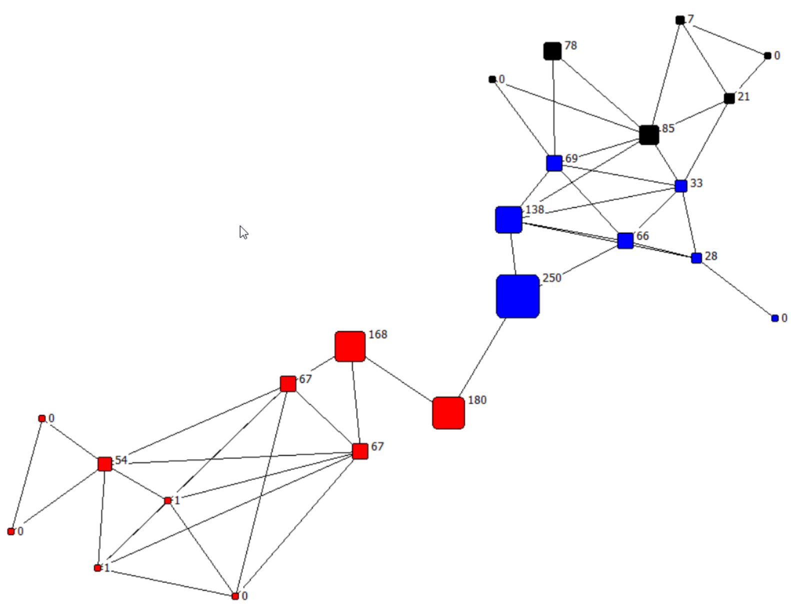

Figure. 3. Betweenness Centrality of the Leading Nodes in the Communities

Conclusions and Discussions

This study identified driving factors that adversely impact critical thinking (reasoning) in learning about Generation Z in the Construction Estimation course through qualitative research. In the assistance-seeking practices, distinct groups are identified: one is seeking in-person assistance and the other is seeking online assistance. The two distinct groups show different types of adverse impacts on learning; online assistance seeking coupled with the lack of construction fundamentals and limited understanding of construction project documents led to adverse impacts on learning. Although students in this community try to learn by spending time on tasks, their work is not fruitful. It is reasonable to suggest that students try to learn, but it is skeptical whether they are actually moving toward the right direction.

Educating students to be equipped with the basics of construction fundaments is essential; obstacles identified are related to the fundamental knowledge in construction. When students are knowledgeable enough in construction fundamentals, they are able to think, reason, and make judgments in their learning activities. In addition, having metacognition questions can be a good strategy. Metacognition questions provide students with self-assessment, which promotes active learning. They also give a chance to instructors to assess whether their educational services work as intended, which makes ever-improving educational experiences for students.

References

An, M. S., & Ryoo, B. Y. (in review). *Critical thinking skills of Generation Z in construction education classroom I: Process/Data-oriented reasoning and judgement*.

Andheska, H., Suparno, S., Dawud, D., & Suyitno, İ. (2020). Writing motivation and the ability in writing a research proposal of generation Z students based on cognitive style. *Journal for the Education of Gifted Young Scientists, 8*(1), 87-104.

Borgatti, S., Everett, M., & Freeman, L. (2002). UCINET for Windows: Software for social network analysis.

Caratozzolo, P., & Á, Á. (2018, 12-16 Nov. 2018). *A new transdisciplinary approach to foster soft skills in engineering : Using critical reading micro-workshops.* Paper presented at the 2018 World Engineering Education Forum - Global Engineering Deans Council (WEEF-GEDC).

Chicca, J., & Shellenbarger, T. (2018). Connecting with Generation Z: Approaches in nursing education. *Teaching and Learning in Nursing, 13*(3), 180-184. doi:https://doi.org/10.1016/j.teln.2018.03.008

Cilliers, E. J. (2017). The challenge of teaching generation Z. *PEOPLE: International Journal of Social Sciences, 3*(1), 188-198. doi:https://doi.org/10.20319/pijss.2017.31.188198

Clarke III, I., Flaherty, T. B., & Yankey, M. (2006). Teaching the visual learner: The use of visual summaries in marketing education. *Journal of Marketing Education, 28*(3), 218-226.

Coelho, P. C. (1998). The Internet: Increasing information, decreasing certainty. *JAMA, 280*(16), 1454A-1454A. doi:10.1001/jama.280.16.1454

Dada, D., Seifan, M., & Berenjian, A. (2020). The Effect of Real and Virtual Construction Field Trips on Students' Perception and Career Aspiration. *Sustainability, 12*, 1200. doi:10.3390/su12031200

Dede, C. (2005). Planning for neomillennial learning styles. *Educause Quartely, 28*(1), 7-12.

Denzin, N. K., & Lincoln, Y. S. (2011). *The Sage handbook of qualitative research*: sage.

Despalatović, L., Vojković, T., & Vukičević, D. (2014, 26-30 May 2014). *Community structure in networks: Girvan-Newman algorithm improvement.* Paper presented at the 2014 37th International Convention on Information and Communication Technology, Electronics and Microelectronics (MIPRO).

Flood, F. (2020). Silver Tsunami of Retirement: Implications for Consideration.

Francis, T., & Hoefel, F. (2018). True Gen': Generation Z and its implications for companies. *McKinsey, 12*.

Girvan, M., & Newman, M. E. J. (2002). Community structure in social and biological networks. *Proceedings of the National Academy of Sciences, 99*(12), 7821-7826. doi:10.1073/pnas.122653799

Guest, G., Bunce, A., & Johnson, L. (2006). How many interviews are enough? An experiment with data saturation and variability. *Field Methods, 18*(1), 59-82.

Hartman, H. J. (2001). Developing students' metacognitive knowledge and skills. In H. J. Hartman (Ed.), *Metacognition in Learning and Instruction: Theory, Research and Practice* (pp. 33-68). Dordrecht: Springer Netherlands.

Jackson, B. J. (2020). *Construction management JumpStart: the best first step toward a career in construction management*: John Wiley & Sons.

Kennedy, M., Fisher, M. B., & Ennis, R. H. (1991). Critical thinking: Literature review and needed research. *Educational values and cognitive instruction: Implications for reform 2, 2*, 11-40.

Kuckartz, A. M., & Kuckartz, U. (2002). Qualitative text analysis with MAXQDA. In: Fundación Centro de Estudios Andaluces.

Lai, E. R. (2011). Critical thinking: A literature review. *Pearson's Research Reports, 6*(1), 40-41.

Leiner, B. M., Cerf, V. G., Clark, D. D., Kahn, R. E., Kleinrock, L., Lynch, D. C., . . . Wolff, S. (2009). A brief history of the Internet. *ACM SIGCOMM Computer Communication Review, 39*(5), 22-31.
Marjaei, S., Yazdi, F. A., & Chandrashekara, M. (2019). MAXQDA and its application to LIS research. *Library Philosophy and Practice*, 1-9.
Masuku, M. M. (2021). Emergency remote teaching in higher education during COVID-19: challenges and opportunities. *International Journal of Higher Education*.
Mathiasen, H., & Andersen, H. L. (2020). Development of Critical Thinking in Higher Education. *Journal of European Education, 10*(1-2), 38-52.
Merriam-Webster. (Ed.).
Patton, M. Q. (2005). Qualitative research. In *Encyclopedia of Statistics in Behavioral Science*.
Prager, F., Rhoads, M., & Martínez, J. N. (2022). The COVID-19 economic shutdown and the future of flexible workplace practices in the South Bay region of Los Angeles County. *Transport Policy, 125*, 241-255. doi:https://doi.org/10.1016/j.tranpol.2022.06.004
Rädiker, S., & Kuckartz, U. (2020). *Focused analysis of qualitative interviews with MAXQDA: Step by step* (1st ed.). Berlin: MAXQDA Press.
Rothman, D. (2016). A Tsunami of learners called Generation Z. In.
Seemiller, C., & Grace, M. (2016). *Generation Z goes to college*: John Wiley & Sons.
Seemiller, C., & Grace, M. (2017). Generation Z: Educating and engaging the next generation of students. In *About Campus* (Vol. 22, pp. 21-26).
Seemiller, C., & Grace, M. (2019). *Generation Z : a century in the making*: Routledge.
Smith, B. (2018). Generalizability in qualitative research: misunderstandings, opportunities and recommendations for the sport and exercise sciences. *Qualitative Research in Sport, Exercise and Health, 10*(1), 137-149. doi:10.1080/2159676X.2017.1393221
Tanner, K. D. (2012). Promoting student metacognition. *CBE—Life Sciences Education, 11*(2), 113-120. doi:10.1187/cbe.12-03-0033
Vasilevski, N., & Birt, J. (2020). Analysing construction student experiences of mobile mixed reality enhanced learning in virtual and augmented reality environments. *Research in Learning Technology, 28*.
Wolff, R. (2021). 8 Great tools to perform qualitative data analysis in 2022. Retrieved from https://monkeylearn.com/blog/qualitative-data-analysis-software/

1 page summary of review Comments and how I addressed

REVIEW 1	
Writing - unclear of the authors definition of "Critical Thinking".	• Added the definition of "critical thinking" in the introduction and in the literature review
Title, Abstract, Keywords - unclear of the authors definition of "Critical Thinking".	• Added the definition of "critical thinking"

REVIEW 2	
Writing - grammatical and syntax errors	• Corrected grammar and syntax errors
Contribution - address how this research adds to the body of knowledge more succinctly	• Addressed the comments in the conclusions and discussions.
Literature Review - The current version does little to instill a sense that the topic has been exhaustively explored	• Literature review has been rewritten reflecting the comments.
Organization - more headings and subheadings is encouraged	• More headings and subheadings are used.
Methodology - how the data was acquired and how the results can be validated is needed	• Data acquisition is explained (interview) • How to recruit interviewees is explained: purposive sampling • How many interviews are done – explained using a reference (Guest, Bunce, & Johnson, 2006) • This paper covered the qualitative data analysis.

REVIEW 3	
Formatting - "FIG. X" when labelling their figures rather than "Figure X".	• Changed to Figure X
Writing - grammatical errors & a paragraph is repeated in the literature review that was in the introduction	• Corrected grammar and syntax errors
Contribution - the paper does not present a clear description of an investigation that does this	• Addressed the comments in the results and conclusions and discussions.
Title/Abstract/keyword - the paper really does not show anything about critical thinking.	• Why the title, abstract, and keywords have "critical thinking" is explained in the introduction.
Organization – content repetition	• The repetition has been removed.
Methodology – confusing, sufficient sample size	• Added the rational for the sample size with a reference of Guest et al (2006) • Covering the Girvan Newman algorithm and the Graph theory becomes another paper, which is out of the scope. • Explaining MAXQDA and UCINET is comparable to explaining SPSS or Revit, which is out of the scope.

Causes of Cost Overruns due to Outsourced Labour – Subcontractor's Perspectives

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Project cost overrun is a significant concern in construction. Statistics reveal that more than 80% of construction projects have not been completed on agreed time or budget due to numerous factors. In the context of the UK construction industry, the subcontractor led approaches are highly encouraged to absorb their expertise and knowledge into the field, which will help projects to complete on time, cost and quality. However, most of the subcontractors are highly reliant on outsourced/external labour. Literature acknowledges the conflicts between main and sub-contractor as one of significant causes for cost overruns and further explains these are mainly due to the issues of sub contractor's labour. However there is limited research on the impacts of outsourced labour in subcontractor's cost overruns. Therefore, this research aims to bridge this gap by identifying the causes of cost overruns due to external labour. Apart from the literature review, the data was collected from a case study of a drywall subcontractor. As part of the case study, six construction professionals of the selected subcontractor were interviewed and thematic analysis was adopted to analyse the data. The results revealed; high wastage, poor workmanship and frequent rework, low productivity, issues with buildability and dayworks as the main causes for cost overruns due to outsourced labour. Moreover, subcontractors are averse to enforce strong performance measures on the outsourced labour due to the fear of low retention.

Key Words: Subcontractor, Cost Overrun, Outsourced Labour, Drywall Construction, UK

Introduction

Construction industry has been facing huge cost and time overruns, affecting all stakeholders (Alshihri, Al-Gahtani and Almohsen, 2022). During the past 70 years, either cost escalations have not decreased or construction cost estimates have not been improved (Herrera, Sánchez, Castañeda and Porras, 2020). This phenomenon is so rooted within the industry that it becomes a matter of routine where project managers try to protect themselves with an extra budget to cover such overruns. The Project finance is the significant element of the construction business, where financial risks and uncertainties pose challenges in project cost planning, which is critical for any organisation to succeed (Odeyinka, Lowe and Kaka, 2008). The UK construction industry encourage the subcontractor led approaches in construction to absorb their expertise and specialisations in to the projects, to ensure on time, cost and quality delivery. However, most of the subcontractors are highly reliant on outsourced/external labour and this issue has been contributed to subcontractor’s cost overruns in numerous ways. Literature explains the cost overruns of principal (main) contractor, however limited attention has been paid to explore the cost overruns of subcontractors’ especially due to outsourced/external labour. The ‘outsourced labour’ considers within this paper refers to the hiring of required labour (skilled/semi-skilled) outside a company to perform services or create goods that were traditionally performed in-house by the company's own employees and staff. They can be freelance or hired through a third party/agency. This preliminary investigation was limited to drywall construction context only as majority of the building projects in the UK involves drywalls and relatively few studies have been examined labour productivity within this trade, where this study aims to bridge the gap.

Literature Review

The structure of the UK construction supply chain consists of several tiers, where the main contractor is clustered under Tier 1, and subcontractors are from Tier 2 and beyond (Department of Business, Innovation and Skills, 2013). In specific to building construction context, there are large number of trades and 80% of those trades/activities are undertaken by the subcontractors (Hinze and Tracey, 1994). In practice, the qualified sub-contractors are hired to perform specific tasks on a project due to their specialty, able to complete work quickly and a lesser cost than the main contractor (Arditi and Chotibhongs, 2005). The construction industry is experiencing cost overruns on a regular basis (Aljohani, Ahiaga-Dagbui, and Moore, 2017). Therefore, exploring the factors that influence the cost overruns of construction is vital in seeking the potential improvements of the industry. Literature acknowledge, contract award to the lowest bidder (Park and Papadopoulou, 2012), design related issues (Herrera, Sánchez, Castañeda and Porras, 2020), conflicts between parties (Keng, Mansor and Ching, 2018), cash flows and financial issues (Memon, Rahman and Aziz, 2012), unrealistic contract duration (Memon, Rahman and Azis, 2011), inaccurate cost estimates (Ammar, Abdel-Monem and El-Dash, 2022), price escalations and wastage (Wanjari and Dobariya, 2016; Herrera, Sánchez, Castañeda and Porras, 2020) are common and frequent causes for cost overruns in construction.

Above those, the shortage of skilled labour (Mahamid, 2017), and low labour productivity (Williams and Anderson, 2016) have been identified as two of significant issues in the construction, even though the industry is promoting the digital technologies. In the current supply chain, the subcontractor tend to sub-subcontract some of their works to other subcontractors, where the subcontractor is responsible for the productivity issues of the construction (Arditi and Chotibhongs, 2005). Even though, this arrangement has formed some convenience to the subcontractors, they are experiencing number of challenges in finding the appropriate sub-subcontractors (skilled labour trades). Such shortage will lead to low productivity and work quality and, subsequently, lead to delays and disputes. Despite the significant influence of subcontracting on-site productivity, this aspect has been omitted in construction productivity related literature. Possible explanations are that subcontractors collectively fit in the contractor's conceptual category within the research framework, or the volume of subcontracted work is kept to the minimum (Hsieh, 1998).

Research Methodology

Literature review was undertaken to identify the cost overruns in construction projects in general as well as in particular to the UK construction context. The intent was to identify the causes and effects of subcontractor’s cost overruns due to outsourced labour/sub-subcontracting of skilled labour. Case study approach was adopted to study the problem in detailed. The selected case provided a good platform to study the problem appropriately as it was heavily impacted the cost overruns and fully dependent on the outsourced labour. Relatively, the subcontractor permitted the access to required data (project information, cost information, issues etc) which was another reason to select this case study. The case was based in the North West of England and the Drywall construction package was examined, which has been assigned to a subcontractor who used to hire the labour externally. The case was reviewed in detailed with a six (6) interviews among the subcontractor's employees to understand the nature/type of cost overruns and the causes and effects of outsourced labour.

Data Collection and Analysis

The selected case was a five-story Nursing Home project located in Liverpool City Centre, UK. Structural frame, external façade and roof, have been completed in prior to drywall construction. The contract duration of the drywall package was 26 weeks. Two (2) project managers (PM1 & PM2), two (2) quantity surveyors (QS1 & QS2), and one (1) operational director (OD) took part in the interview process as they were currently engaged on that project. In addition to those five interviewees, a project manager (PM3) working for the same sub-contractor but had no engagement within the selected case also interviewed. The interview template was developed and 1 pilot interview was undertaken to check the readability and the clarity of the questions. With that minor amendments were considered in the two questions. All interviews were recorded and transcribed appropriately and analysed thematically. In spite of the fact that some of the themes had been created prior to interviews, new themes emerged, completely overshadowing previously developed themes. More than 60 nodes were developed during the coding process, which was further winnowed down and combined in to new themes.

Results and Discussion

Cost overruns associated with the main contractor and subcontractors are typically overlooked within the recent literature. Hence this section tunneled through to the causes of sub-contractors' cost overruns due to outsourced/externally hired labour with an appropriate case study of drywall construction. The drywall package of the selected case study was undertaken by the selected sub-contractor and it was a labour intensive package. The sub-contractor hired the labour from an agency and also for some of the tasks of the drywall package was completed by the freelance/self-employed labour. Even though there were some pre-established protocols to control the cost overruns, the package itself exceeded 20-30% of cost. This was identified through the interviews and the following causes of cost overruns were derived through the analysis of verbatim.

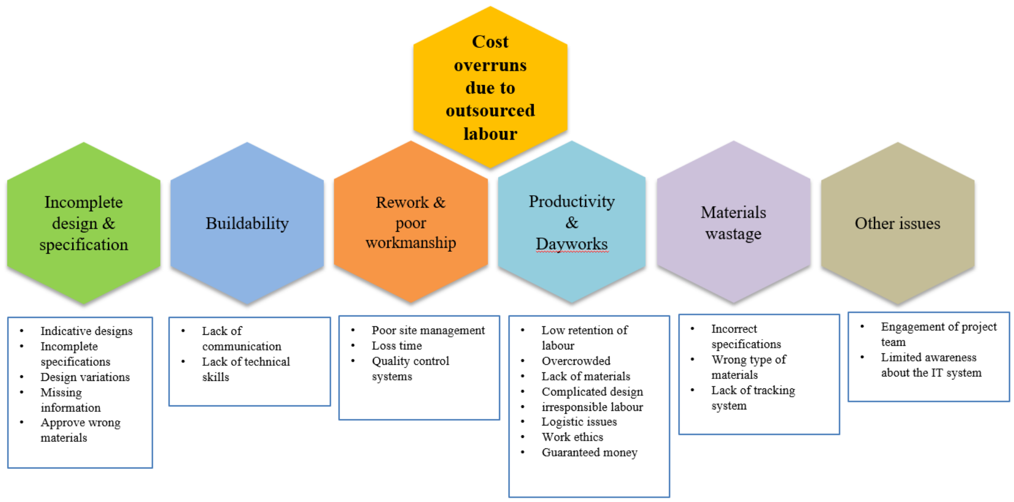

Figure 1. Causes of cost Overruns due to outsourced/externally hired labour for drywall construction

Altogether 6 themes (incomplete design and specifications; buildability, rework and workmanship; productivity and dayworks; materials wastage, and other) were identified as the main causes for sub contractors' cost overruns due to outsourced labour. The detailed analysis identified the sub causes of the issue and listed under each main cause.

Incomplete Design and Specifications

Herrera, Sánchez, Castañeda and Porras (2020), Memon, Rahman and Aziz (2012) explained that incomplete design at the time of tender is one of common causes of cost overruns in construction projects. In the context of drywall construction the subcontractor involvement can occur at any point during the construction process, depending on when the tendering process begins. All the interviewees from the drywall subcontractor's claimed that when a subcontractor enters in to the tendering stage, the drawings were not fully completed and it is relatively rare that the project is fully designed. One of Project managers (PM1) stated that "the drawings change all the time and you got to work with something to tender for the job" and operational director (OD) noted "normally it is more like a concept or an indicative design". It is assumed that the experienced subcontractor will understand and visualize the job before detailed drawings and specifications are prepared. However PM2 said "we are normally aware of the size and type of building that we are going to tender but they will use that to start with", and one of quantity surveyors (QS2) corroborates "so you would make an assumption, and qualifications list qualifying your tender basically so my price allows for this, it does not allow that, then there maybe request for information before you complete the tender in order, it's all about qualified details if something's missing or not there".

In addition to design changes, the incomplete material specifications and/or approving a wrong material at the tender stage have created substantial cost overruns to drywall construction. PM2 stated "the tender stage is obviously if we go to build something that's not quite right then we aren't building to what we tendered for and then it's up to the client to revalue it". Supportively PM1 noted "it's not identified at this instance, it's a specific type of stuff that may be used in a specific instance at the wrong time or it's the wrong type that's identified, so that could happen". Therefore it is evident that most of the designs and specifications are at the developing stage when the drywall subcontractors are enter in to the contract which have been created a sequence of cost overruns.

Buildability/Constructability

Incorporation of buildability improves the construction project performance in terms of its cost, quality, productivity, safety, and results early completion (Wimalaratne, Kulathunga and Gajendran 2021). However if the design is limited in buildability aspects, cost overruns are highly likely. In drywall construction, the subcontractors face buildability issues more frequently. As per interviewee PM2, “well, that is a design issue so as a sub-contractor without design, that is not our reliability, our job is to drawings and to build as you are told”, buildability is a good example where it can potentially take longer to build than first anticipated. QS2 stated “if you can not do it as you are told then it is a change and there comes your delay, potentially”. Even though in such instances when buildability is not possible to achieve at first instances it does become a variation, as P3 explained “but we would probably press that to change and become a variation to the contract”. It is true that a subcontractor can recover costs in such processes. However, the decision-making process and correspondence between a principal contractor and a subcontractor take considerable time. A project manager who has to deal with poor decision-making places strain to allocate new work for skilled workers who came to work to make money and not sit and wait for it. PM1 explained, “I mean that’s what I don’t want to happen, so I try to avoid downsides. I always try to keep people busy”. Such lack of coordination between parties does result in cost overruns.

Rework and Poor Workmanship

Rework and poor workmanship also contributes to cost overruns in construction (Memon, Rahman and Azis, 2011; Shanmugapriya and Subramanian, 2013). Supportively, QS1 states, “I’m guessing we’ve probably spent half a million pounds (maybe more than that through)”, that’s the amount of the money that was spent last year on reworks in just one project. It is a major contributing factor to cost overrun. However, it is not always clear at first instance where it does originate from. Mansur, Zin and Linbo (2019) argue poor site management and supervision are another causative factors leading to construction cost overruns. During the interview process, QS2 outlines “there’s an element of design and management in there because you need a good site manager to issue drawings in a timely manner to explain details”. Throughout the literature, such poor workmanship is attributed to the shortage of skilled labour, which leads to cost overrun (Baloyi and Bekker, 2011; Memon, Rahman and Aziz, 2012). Such poor workmanship happens despite the fact that quality control procedures are in place that allow for the identification of poor workmanship in the beginning. PM1 states, “certainly we use IT to help for our quality control systems,” and furthermore “we’re finding better ways of monitoring the work, documenting the work, documenting the issues, documenting the delays”. PM2 explains “you got all the quality control portals and evidence pictures, so such changes did not happen overnight and were slowly implemented”. In addition to QS1 noted “over 10 years our IT systems have changed dramatically, we have web-based and app-based software to do our quantity checks”. Literature argue that lack of appropriate software as a factor inhibiting effective project cost control (Olawale and Sun, 2010). In a probe question on how often poor workmanship happens, PM2 responded “If I was honest, probably every week because in the dry-lining world it’s classed as a semi-skilled job, not a skilled trade”. As a result of poor workmanship, there is a direct impact on the costs incurred by the subcontractor, as time and money must be spent to resolve the matter.

Productivity and Daywork

Most of the skilled workers involved with this subcontractor are self-employed or hired through a third party/agency. Certainly, it does provide some advantages as noted by QS2 “if quality still not there, replace the labour with someone different”. However, QS1 mentioned, “you have more control over your employee”, meaning self-employed today is here, but tomorrow might be gone to a different project where the pay is better, therefore leaving subcontractor without a workforce. According to PM3, productivity is measured against a program “we have a program that works, and the labour histogram, so we compare the two and measure it in time,” essentially by the amount of work done. Despite how much money skilled workers are getting paid, productivity can be affected by various reasons, such as lack of materials, poor quality of the workforce, complicated design and overcrowding due to other trades. PM2 outlines that in the current market, logistical problems with material delivery is a concern “so at the moment a lot of British gypsum and Siniat etc. are struggling to bring all materials out”.

Daywork was highlighted as another cause for low productivity. There are various reasons why daywork is authorised; something that has been overlooked or missed during a tender stage, where the principal contractor asks to supply skilled workers for some rectifications that they are liable for drywall. QS1 stated that “Probably, if I put a number on it, we would get 60% productivity on daywork instead of price”. On the other hand PM2 argued “day rate, productivity goes down mainly because the guys know that the money’s guaranteed. Therefore, it all comes down to the person and his attitude and work ethic that he is willing to bring to the site. QS2 mentioned that “you have people that stand around doing nothing as they’re on the day rates”. Low labour productivity is one of the influential factors for cost overruns (Mansur, Zin and Linbo, 2019).

Material wastage

Construction is identified as a high waste generating sector. Similarly within this case analysis QS1 stated “One of the biggest problems we have is waste”, within a span of few months from when the project was initiated, up to the date of the interview, hundred tons of just plasterboard waste been generated and PM2 contributed by stating that “we’ve had 24 skips, they weigh 4 tons each”. However, these numbers come from the skip supplier after they issue the certificate, but how much gets thrown away just by skilled workers of materials that can be used in the future is still unclear. Furthermore, there is no system to track how waste is generated on-site and by which work crew. In contrary PM3 said that we have a system in place for our pricing work, we will know how much material will be wasted so all that will be accounted for in the budgets”. As mentioned earlier, poor workmanship contributes to waste, not only material waste but also a lost time, thereby leading to cost overruns.

Other related Issues

The findings clearly explain that the project manager was not consulted during the bidding process but only offer advices when once the project has commenced. PM2 states, “because quantity surveyor knows what they need to get done but occasionally I might get a phone call about a certain material or a certain piece of plan”. Where QS2 states, “job of an estimator and a QS is quite different and in different detail, I would estimate a price change, variation, small works, I would never tender for a million-pound project”. This finding correlates with Akintoye and Fitzgerald (2000), who outlines that site management’s involvement in cost estimating is minimal. In addition, the findings of the case reveal that the subcontractor heavily invest in IT, including quality control software, web-based estimation software, as well as for tender and measurement purposes. However, at the same time, all technical support is sourced from a third-party company. The participants did not mention any in-house software that was developed specifically for their organization. For example, to track the productivity of skilled workers on a daywork, or how much waste is generated by a specific task or a person, it would be possible to compare with other projects. Therefore, the level of the investment is inconclusive, especially when most of the labour is outsourced.

Conclusions

The UK construction industry has many inherent risks, even though the risks are well known, many companies are still engaging in the construction process and trying to minimise, share or transfer the risks to the appropriate parties. The paper identified the subcontractor's perspectives on causes of cost overruns in construction due to outsourced labour. The findings reveal that poor tender documents issued by the subcontractor as a major cause for cost overruns, hence , they engage in a tendering process by relying on their knowledge and experience. The magnitude of the problem increase when the labour element has been added into the formula where they have ignored it at the first instance. Evidently, poor attitude and negligence of outsourced labour result in excessive material use on site. Incomplete drawings or complicated designs cause skilled workers to pack up their tools and leave the site, leaving the subcontractor with low productivity while new workers are introduced. Moreover, there is no guarantee that the new workforce will remain on-site, resulting in the subcontractor employing agency workers on a day-to-day basis. As a result the daytime productivity becomes significantly less and critical. Although some of the cost overruns have occurred due to inefficiencies of principal contractor or consultant where money could be recovered through contract mechanisms, however not all variations will result in the extension of time, therefore increasing the pressure on the subcontractor to complete the project. Construction waste occurs as a result of poor worker skills and excessive housekeeping requirements by the principal contractor when materials that may have been used are disposed. Despite such material waste, there is still a lack of appropriate software that could help minimize waste within the drywall business, and the outsourced labour does not seem to care how much waste they generate. Therefore, use of standard estimating procedures, which are found in most textbooks, are inadequate. Furthermore, the unknown nature of outsourced labour makes cost control against the specified budget unrealistic. Findings within the research suggest that the drywall industry lacks more rigid material waste control procedures, and developing suitable software would be beneficial not only for the industry but also for the environment. Developing material waste awareness training for the outsourced labour within the industry is also recommended. The study was limited to a single case study of drywall construction due to restrictions of the time and accessibility of data.

References

Ahiaga-Dagbui, D.D and Smith, S.D (2014), Rethinking construction cost overruns: cognition, learning and estimation, Journal of financial management of property and construction, 19(1), 38-54.

Akintoye, A. and Fitzgerald, E. (2000), A survey of current cost estimating practices in the UK. Construction Management & Economics, 18(2), 161-172.

Aljohani, A. (2017). Construction Projects Cost Overrun: What Does the Literature Tell Us? International journal of innovation, management and technology, 137-143.

Alshihri, S, Al-Gahtani, K, Almohsen, A (2022), Risk factors that lead to time and cost overruns of Building Projects in Saudi Arabia, Buildings 2022, 12(7), 902.

Ammar, T; Abdel-Monem, M and El-Dash, K (2022), Risk factors causing cost overruns in road networks, Ain Shams Engineering Journal, 13(5).

Arditi, D. and Chotibhongs, R (2005), Issues in subcontracting practice. Journal of Construction Engineering and Management, 131(8), 866-876.

Baloyi, L. and Bekker, M. (2011) Causes of construction cost and time overruns: The 2010 FIFA World Cup stadia in South Africa. Acta Structilia: Journal for the Physical and Development Sciences, 18(1), 51-67.

Behling, F. and Harvey, M (2015), The evolution of false self-employment in the British construction industry: a neo-Polanyian account of labour market formation. Work, Employment and Society, 29(6), 969-988.

Department of Business, Innovation and Skills (2013), Supply Chain Analysis in to the construction industry, BIS Research Paper No 145, London, UK.

Herrera, R.F.; Sánchez, O.; Castañeda, K and Porras, H (2020), Cost Overrun Causative Factors in Road Infrastructure Projects: A Frequency and Importance Analysis. Applied Science, 10, 5506. https://doi.org/10.3390/app10165506

Hinze, J and Tracey, A (1994), The contractor-subcontractor relationship: the subcontractor's view. Journal of Construction Engineering and Management, 120 (2), 274-287.

Hsieh, T.-Y. (1998) Impact of subcontracting on site productivity: lessons learned in Taiwan. Journal of Construction Engineering and Management, 12 (2), 91-100.

Keng, T.C., Mansor, N. and Ching, Y.K (2018), An Exploration of Cost Overrun in Building Construction Projects. Global Business & Management Research, 10(3).
Love, P.E and Li, H. (2000), Quantifying the causes and costs of rework in construction. Construction Management & Economics, 18(4), 479-490.

Mahamid, I (2017), Analysis of common factors leading to conflicts between contractors and their subcontractors in building construction projects. Australian Journal of Multi-Disciplinary Engineering, 13(1), 18-28.

Mansur, S.A., Zin, R.M. and Linbo, L (2019), Components of Cost Overrun in China Construction Projects. IOP Conference Series: Materials Science and Engineering Conference.

Memon, A.H., Rahman, I.A. and Azis, A.A.A. (2011), Preliminary study on causative factors leading to construction cost overrun. International Journal of Sustainable Construction Engineering and Technology, 2(1).

Memon, A.H., Rahman, I.A. and Aziz, A.A.A (2012), The cause factors of large project's cost overrun: a survey in the southern part of Peninsular Malaysia. International Journal of Real Estate Studies, 7(2), 1-15.

Nisbet, P (2007), Human capital vs social capital: Employment security and self-employment in the UK construction industry. International Journal of Social Economics, 34(8), 525-537.

Odeyinka, H.A., Lowe, J. and Kaka, A. (2008), An evaluation of risk factors impacting construction cash flow forecast. Journal of financial management of property and construction, 13(1), 5-17.

Olawale, Y.A. and Sun, M. (2010) Cost and time control of construction projects: inhibiting factors and mitigating measures in practice. Construction Management and Economics, 28(5), 509-526.

Park, Y.I. and Papadopoulou, T.C (2012), Causes of cost overruns in transport infrastructure projects in Asia: their significance and relationship with project size. Built Environment Project and Asset Management, 2(2), 196-216.

Philips-Ryder, M., Zuo, J. and Jin, X.H. (2013) Evaluating document quality in construction projects–Subcontractors' perspective. International Journal of Construction Management, 13 (3), 77-94.

Shanmugapriya, S. and Subramanian, K. (2013) Investigation of significant factors influencing time and cost overruns in Indian construction projects. International Journal of Emerging Technology and Advanced Engineering, 3(10), 734-740.

Tejale, D.S., Khandekar, S. and Patil, J (2015), Analysis of construction project cost overrun by statistical method. International Journal, 3(5), 349-355.

Wanjari, S.P. and Dobariya, G (2016), Identifying factors causing cost overrun of the construction projects in India. Sādhanā, 41(6), 679-693.

Williams, G.H. and Anderson, T.R (2016) Impacts to productivity in metal stud framing, and the hanging and finishing of gypsum drywall. 2016 Portland International Conference on Management of Engineering and Technology (PICMET) Conference.

Wimalaratne, P.L.I., Kulathunga, U. and Gajendran, T (2021) Comparison between the terms constructability and buildability: A systematic literature review. In: Sandanayake, Y.G., Gunatilake, S. and Waidyasekara, K.G.A.S. (eds). Proceedings of the 9th World Construction Symposium, 9-10 July 2021, Sri Lanka. 196-207. DOI: https://doi.org/10.31705/WCS.2021.17.

Winch, G (1998) The growth of self-employment in British construction. Construction Management & Economics, 16(5), 531-542.

Dear respected reviewers,

Please find attached the revised version of the manuscript titled *An Overview of the Application of Performance Based Specifications in Concrete Construction Projects*. The following revisions were included:

1. Figures and captions are centered
2. Formal literature review section is added in the paper
3. Research methodology section is included to clearly states the research objectives and methodology followed throughout the paper
4. Additional citations are added to the body of the manuscripts and the reference section
5. Paper format, grammar, and sentence structure are revised
6. Table 1 listing definitions and interpretation of different codes to performance-based specifications is added to the manuscript
7. Table 2 with a list of performance evaluation criteria is added to the text.
8. A case study section describing how the use of performance-based specifications could add flexibility to the design of green concrete (to increase project sustainability). A list of design parameter limitations is included in Table 3 (within the case study section).

An Overview of the Application of Performance Based Specifications in Concrete Construction Projects

Construction projects use prescriptive codes to regulate multiple stages of concrete construction activities. Prescriptive codes are suitable for design-bid-build projects as it provides sufficient details for different project parties. Despite of its advantage, prescriptive codes represent an impediment to the potential improvement of concrete mix characteristics, including immediate mix properties, long-term performance, and concrete sustainability due to the restrictions imposed on material selection, constituent proportions and batching and mixing procedures. To improve construction projects quality and long-term performance, current federal legislatures focus on the replacement of prescriptive codes with performance-based specifications, where the concrete mix is designed and optimized to attain specific long-term performance criteria decided according to the project service conditions. This research paper presents the possible outcomes of utilizing performance-based specifications in replacement of prescriptive codes in concrete construction; and presents the changes to be adopted in project quality control procedures to ensure its successful implementation in future projects. The results of this research show that performance-based specifications are advantageous in fast-track projects, including design-build project delivery. Concrete mixes produced according to performance-specs have superior long-term performance characteristics, higher durability, and improved sustainability. Due to the increased durability, structural concrete designed and poured using performance specs need lower maintenance intervention, which reduce construction projects life cycle cost.

Keywords: Prescriptive codes, Performance-based specs, Long-term performance, Durability, Life cycle cost.

Introduction

The construction industry comprises approximately 9% of the national gross domestic product (GDP) of the United States. Approximately 1.8 trillion dollars per calendar year is spent in construction projects including residential, commercial, heavy, and industrial projects in the local market (Akhnoukh, 2020). The construction industry utilizes different codes and specifications to control different construction activities; and provide guidelines to regulate the relation between different stakeholders of the construction project including the project owner, architect, project consultant, general and sub-contractors, and the construction manager. Different types of codes and specifications are available to provide different trades with design aids and charts to design different components of the construction projects, provide material specifications, regulations for the construction procedures, and site safety. Codes and specifications provides minimum provisions to ensure the safety and serviceability of the construction project.

In today's construction market, concrete is used in almost all stages of construction including the construction of different types of foundation, and in multiple stages of the super structure including the construction of columns, beams, girders, and slabs. Due to its market share, concrete is considered the dominant construction material. Several codes and specifications are used by design engineers, consultants, contractors, and construction managers to regulate their concrete construction activities, including American Concrete Institute (ACI) Codes, American Society of State Highways and Transportation Officials (AASHTO) Specifications, Precast/Prestressed Concrete Institute (PCI).

Specifications, and American Society for Testing and Materials (ASTM). The afore-mentioned codes and specifications are classified as prescriptive codes. Prescriptive codes are legal documents that prescribes a rigid description for the design and construction of the projects. In plain, reinforced, and prestressed concrete construction projects, a prescriptive code provides a specific concrete mix design including the proportions of mix constituents, minimum and maximum water-to-cement ratio, approved ranges for sieve analysis results of fine and coarse aggregates, and a detailed mixing and curing procedures. Prescriptive codes supply different project stakeholders with a set of fresh and hardened concrete testing to evaluate the produced concrete as slump testing for fresh concrete (ASTM C143, 2015), and compressive strength testing for hardened concrete (ASTM C39, 2018).

The compliance of project stakeholders and construction parties (design engineer, project manager, and contractors) with prescriptive codes provisions results in a successful completion of the construction project. The rigid provisions provided by prescriptive codes minimize potential conflicts during different activities execution. Despite these advantages, prescriptive codes provide a limitation to the ability of different parties within the project to use innovative approaches in executing their work. In addition, prescriptive codes predate new construction concepts including LEAN construction, construction sustainability, and ultra-high-performance materials. To-date revised prescriptive codes do not include performance-based provisions for concrete design. Thus, prescriptive codes don't provide sufficient flexibility in utilizing these new construction concepts, which adversely affects the project long term performance, life cycle cost, and sustainability.

History of Design Codes in Construction Industry

The concept of Building Codes evolved thousands of years ago to support proper construction and rebuilding. Building codes were mainly developed to increase the safety and ensure the longevity of any construction project. The oldest code relevant to construction is known as Codes of Hammurabi. The Codes of Hammurabi, developed 2000 BC, states the following "In the case of collapse of s defective building, the builder is to be put to death if the owner is killed by the accident; and the builder's son if the son of the owner loses his life". In 341 BC, a different code evolved, known as Code of Socrates. Socrates code states the following "He shall set the joists against each other, fitting, and before inserting the dowels he shall show the architect all the stones to be fitting; and shall set them true and sound and dowel them with iron dowels, two dowels to each stone". Hammurabi and Socrates codes are the oldest known construction codes that targeted the regulation of construction projects and provided limited provisions to assist project stakeholder in job execution.

In modern history, building codes evolved with more provisions and specifications. The increase in code details is attributed to the nature of stakeholders participating in codes development including: 1) insurance industry: and its main purpose of providing standards to eliminate accidents, 2) local government: that target the development of regulations to deliver safe and economic projects for the welfare of its citizens and taxpayers, and 3) social organizations: which target the minimization of project impacts on the environment. The modern building code's main objective is to provide minimum provisions to ensure the structural integrity and proper use of construction materials without violating the predefined project budget and schedule.

To avoid construction conflicts and possible legal issues, modern codes provides strict provisions to follow during the project design (design codes) and during different projects construction phases (construction codes). Design and construction codes have built-in factors of safety to avoid potential failures under unforeseen events including extreme loading conditions, possible human errors in design and construction, and finally to account for potential flawed construction materials. The strict provisions and clauses qualified current design and construction codes to the term "prescriptive codes."

Literature Review

The perspective approaches are perceived as old and reliable methods of design in general, and for concrete mix design in specific. However, prescriptive codes and specifications are considered conservative, and may result in the consumption of larger amount of cement which negatively impacts the environment (Akhnoukh, 2018, Elia et al., 2019). Prescriptive codes and specifications for concrete mix designs focus on mix constituent selection, materials proportions, batching, mixing, pouring, compaction, and curing of concrete mixes. Concrete quality is primarily evaluated by measuring hardened concrete compressive strength. Recently, researchers have made significant progress in developing mixes with ultra-high compressive strength (Akhnoukh, 2021, 2020, 2019, 2013, and 2010). However, the ultra-high strength of developed mixes did not always translate to improved long-term performance (durability) (Shah et al., 2000). Recent research project showed that concrete problems such as alkali-silica reactivity and chloride ingress in concrete may result in expedited deterioration and premature failure to ultra-high strength concrete (Akhnoukh and Mallu, 2022, and Akhnoukh et al. 2014).). Currently, prescriptive codes assumes that concrete will be durable for its specific service life as long as it meets irrelevant prescriptive criteria as compressive strength (Beushausen and Luco, 2016). The lack of long-term performance evaluation of concrete represents a major deficiency in prescriptive codes (Beushausen et al., 2016).

Unlike the prescriptive codes, performance specifications specify what is required from the concrete on short and long terms. Thus, the primary focus is on the concrete performance rather than on the concrete ingredients. Despite their major advantages, performance-based codes are not widely used in the construction market due to the lack of consensus for the term "Performance Specifications," as it can be interpreted differently (Bickley et al., 2006). Currently, several design codes are predominantly prescriptive. Yet, they have included few explicit guidelines to improve the long-term performance of concrete. Major prescriptive codes with performance-based added provisions are shown in Table 1. (Ali et al., 2021).

Table 1.

Performance specifications definitions according to different codes

Codes	Interpretation
CIB Working Commission W060	The practice of thinking and working in terms of end result and not the means
U.S. Federal Highway Administration	A performance specification define the performance characteristics of the end product and link them to construction
National Ready Mix Concrete Association (NRMCA)	A performance specification is a set of instructions that outlines the functional requirements for hardened concrete
Cement Association of New Zealand	A performance-based specification prescribes the required properties, but does not specify how they are developed.

Objectives and Methodology

The main objective of this research is to highlight the major differences between prescriptive and performance-based codes. This objective is attained by the implementation of the following methodology:

- Performance-based specifications in concrete construction is defined and interpreted
- Performance-based criteria for concrete design is selected and introduced
- Advantages of performance-based specifications are highlighted
- Challenges and limitations to the performance-based specification implementation in current construction market is investigated
- A case study is presented to highlight the major differences between prescriptive and performance-based specifications

Performance-Based Specifications in Concrete Construction

Concrete performance specifications avoid requirements for productivity methods including mixing, pouring, and compaction of concrete. In addition, the performance-based specifications do not limit the mix designer with traditional requirements for the selection of the mix constituents including a minimum or maximum cement content, a maximum content for supplementary cementitious materials (SCMs), a given range for the use of mixing water, and specific mixing time (Foliente, 2000). The move towards performance specifications for concrete projects requires a different quality control approach to assess the compliance of the concrete structures with the new specifications. Thus, traditional quality control techniques followed by prescriptive codes as compressive strength should no longer be used due to their limited ability to predict long-term performance of concrete.

The current attempts to produce performance-based specifications for concrete projects considers different set of tests to estimate the efficiency of the project and the potential performance under specific project criteria. Examples of concrete performance criteria and relevant testing techniques are:

1. Concrete resistivity to chlorides and sulfates: which improves the long-term performance of concrete structures due to the reduced rate of steel corrosion. To attain higher resistivity and lower rate of steel corrosion, concrete voids ratio should be minimized. Currently, researchers are considering electrical resistivity of concrete to assess the concrete voids ratio and their distribution, which can be related to the rate of steel corrosion in future concrete construction projects. The concrete surface electrical resistivity depends on measuring the electric current in Amps passing through the concrete when an electric current source of known potential is known. Surface resistivity testing, shown in Figure 1, is done according to AASHTO T358-17.

Figure 1: Wenner device for surface resistivity measurement

2. Concrete performance under freeze-thaw cycles: which is required in areas where temperatures fluctuate around freezing point. Increased resistivity of concrete requires even dispersion of micro-sized air voids among the concrete surface. Once free water within the concrete mix freezes and its volume increase, the micro-sized air voids can contain the expansion of frozen water particles without inducing internal pressure that cracks the hardened concrete. Current research is investigating the use of a super air meter in replacement to the regular air meter used in current concrete quality control measurements. The super air meter is used to calculate the size and dispersion of air voids within the concrete as compared to regular air meter which measure the overall voids content only.

3. Concrete maturity testing: which is used to estimate the cement hydration process based on the evolved heat as a result of water-cement hydration process. Maturity testing, shown in Figure 2, is done according to ASTM C 1074.

Figure 2: Maturity measurement of concrete (US DOT, 2000)

The afore-mentioned tests represents the main criteria in evaluating the performance of hardened concrete. Additional criteria could be used as shown in Table 2.
Table 2.

Test methods for performance-based specifications of concrete

Test	Description	Standard/Code
Volume of permeable voids	Test for volume of permeable voids	ASTM C642
Accelerated carbonation test	Evaluate carbonation resistance of concrete	ISO 1920 Part 12
Petrographic test	Examines and evaluates microstructures of concrete	ASTM C457
Linear polarization resistance	Measure corrosion rate on steel rebars	RILEM TC 154-EMC
Mass loss test	Determine mass loss due to moisture migration	ASTM C1792
Abrasion test	Assess abrasion resistance	ASTM C944/C779

The performance specifications of concrete require the establishment of a framework to regulate its use in current and future construction projects (Lobo et al., 2006). The established framework should establish standards for concrete production facilities, project requirements that list the expected performance of hardened concrete, a series of field acceptance tests that can assess long-term performance of concrete.

Advantages of performance-based specifications

Performance-based specifications are currently introduced to the construction market to attain specific targets and objectives. Despite their limited incorporation in construction project documentation in today's construction market, performance specifications will be increasingly used in future projects in the local market due to their positive impact on site constructions activities, and the improved future performance of the completed project. The following represents the possible advantages to be attained by the implementation of performance-based specifications in construction projects:

1. Increased flexibility in activities execution. This is attributed to the fact that the success completion of the construction activity will be judged based on specific performance criteria, and not according to rigid production techniques or prescribed instructions.

2. The performance-based specifications are dynamic. It can accept or adopt different project conditions. This flexibility results in a seamless workflow in projects with tight schedules and large number of critical activities.

3. Performance-based specification is mainly concerned with quality of the end product. Taking concrete construction as an example, the application of performance specs results in concrete with higher durability, long-term performance, and improved resistivity to adverse environmental conditions. This leads to project reduced maintenance and a lower life cycle cost.

4. Increased project sustainability is attained due to the reduced waste in construction material. In addition, performance-based specs allow the contractor to use innovative green and economic materials in construction as long as the final required performance is attained.

5. Performance-based specifications are suitable for new and advanced construction techniques as construction using 3-D printers and tilt up structures. In addition, these specifications are advantageous in construction of project with severe loading uncertainty as in blast resistant structures for army and homeland security projects, structures in regions with high seismic activity, and construction in hurricane and tornado affected regions.

Finally, performance-based specs, due to their flexibility, is suitable to new project delivery methods. In recent studies, project delivery methods as design build (DB), integrated project delivery (IPD), and construction management at risk (negotiated work) are increasingly considered in the local construction market. These projects will increasingly utilize performance-based specifications to enable flexible and seamless workflow using minimal hard and prescriptive language during the project activity execution.

Challenges and Limitations of Implementing Performance-Based Specifications

The main advantages of performance-based specifications are exploited when used in construction projects with specific parameters relevant to project nature, loading, and environmental conditions. Despite of their advantage, performance-based specifications are faced with multiple challenges that limits their use on a larger scale in construction projects. The main impediments to the incorporation of performance-based codes in construction projects are:

1. Performance-based specifications do not include rigid guidelines for material production. This might result in increased legal issues among different project stakeholders.

2. Lack of technical knowledge regarding the performance matrix to be used in the assessment of concrete performance.

3. Current material specifications provide adequate provisions to apply prescriptive codes. Additional research, specifications, and guidelines are required to enable project designers and contractors to adopt performance-based specs in their projects.

4. Performance-based specifications are not suitable for all project delivery methods. As an example, performance-based specs are not suitable for design-bid-build projects, where concise and specific and strict language is required.

5. A Lack of quality control testing procedures to be used when performance-based specs are adopted. For example, current quality control procedures for concrete uses slump test for fresh concrete and compressive strength testing for hardened concrete. Both tests are suitable for prescriptive codes. Additional research is required to develop different testing techniques to assess performance-based parameters.

Case Study

The application of prescriptive codes in developing green concrete mix designs will not provide the mix designer with the flexibility to eliminate or substantially reduce the portland cement content within the mix design. On the contrary, performance-based code provides the design engineer with flexibility in material selection, batching, mixing, pouring, finishing and curing. Table 3 compares the impact of different codes on the final sustainability of concrete mix.

Table 3

Comparison of prescriptive and performance-based codes impact on concrete sustainability

Specification Provision	Prescriptive Codes	Performance-Based Codes	Notes
Cement type & source	Restricted	Geopolymers are allowed	Using geopolymers eliminate cement and enhance concrete sustainability
Aggregate type & source	Restricted	Recycled concrete use allowed	The use of recycled building materials add LEED points
Supplementary cementitious materials (SCMs)	Maximum percentage specified	SCM could replace 100% of cement	Higher SCMs percent reduces cement content and increase durability
Mixing water	Potable water required	Possible use of alkaline activators, as in Geopolymers	Mandated use of water will not allow for producing geopolymer concrete with alkaline activators.

Discussions and Conclusions

Most of the current construction projects within the United States utilize prescriptive codes to control and judge different construction activities. Prescriptive codes provide general contractors with solid guidelines in performing their jobs and in the assessment of the quality of the contractor outcomes. Despite their advantages, these codes confine the contractor’s ability in using new technology, new materials, and/or hinders the contractor capabilities in selecting novel approaches in job sites.

Current research is providing the construction market with different reasons to transform the project codes and specifications into performance-based specifications. The major advantages of performance-based specifications include: 1) the flexibility provided to the project designer and contractor to select innovative approaches to design and execute different projects activities, 2) the dynamic nature of performance-based specifications, which allows the project designers and contractors to select their materials, construction methods, and quality control procedures according to the project specific limitations, and 3) performance-based codes and specifications are suitable to the increasingly-adopted design-build project delivery due to its flexible nature.

In this research, the use of performance-based specifications in concrete construction is investigated versus traditional prescriptive codes. The provisions, advantages, and disadvantages of both types in concrete construction activities were investigated including the possible standard testing used to assess the quality of the produced concrete when the two different codes are used. The research findings showed that prescriptive codes could be advantageous in design-bid-build projects where rigid documentation are required, mix constituents should be predetermined for project pricing purposes, and mixing and curing procedures are to be prespecified for the contractor. On the other hand, performance-based specifications advantages were significant when non-traditional projects are considered, including projects affected by large non-conventional loads and stresses resulting from freeze-thaw cycles, length changes due to thermal variations, or extreme environmental attacks from soil and water contamination at the project site.

The research outcomes recommend the implementation of performance-based specifications on a larger scale within the construction market in the United States. Performance-based specification flexibility provides the project designer and contractor with the flexibility needed to improve the quality of the construction project; and improve its long-term performance. Improved project quality results in lower demand for maintenance and repair activity, which reduce the life cycle cost of construction projects.

References

AASHTO T358. (2017) Standard method of test for surface resistivity indication of concrete ability to resist chloride ion penetration, American Association of State Highway and Transportation Officials, Washington D.C., pp. 10

Akhnoukh, A.K., and Mallou, A.R., "Detection of alkali-silica reactivity using field exposure site investigation," Proceedings of the 58th Annual Associated Schools of Construction International Conference, Georgia, 2022

Akhnoukh, A.K., and Buckhalter, C., (2021) "Ultra-high-performance concrete: constituents, mechanical properties, applications, and current challenges," Elsevier Journal of Case Studies in Construction Materials, Vol. 15, https://doi.org/10.1016/j.cscm.2021.e00559

Akhnoukh, A.K., (2020) "Accelerated bridge construction projects using high performance concrete," Elsevier Journal of Case Studies in Construction Materials, Vol. 12, https://doi.org/10.1016/j.cscm.2019.e00290

Akhnoukh, A., (2020) "Advantages of contour crafting in construction applications," Recent Patents on Engineering, Vol. 14

Akhnoukh, A.K., and Elia, H., (2019) "Developing high performance concrete for precast/prestressed concrete industry," Elsevier Journal of Case Studies in Construction Materials, Vol. 11, https://doi.org/10.1016/j.cscm.2019.e00290

Akhnoukh, A.K. (2018), "Implementation of nanotechnology in improving the environmental compliance of construction projects in the United States," Particulate Science and Technology, Vol. (36), No. 3 https://doi.org/10.1080/02726351.2016.1256359

Akhnoukh, A.K., Kamel, L.Z., and Barsoum, M.M., "Alkali silica reaction mitigation and prevention measures for Arkansas local aggregates," International Journal of Civil and Environmental Engineering, Vol. 10, No. 2, 2016, pp. 95-99 doi.org/10.5281/zenodo.1338860

Akhnoukh, A.K., (2013), "Overview of nanotechnology applications in construction industry in the United States," Micro and Nano Systems Journal, Vol. (5), No. 2, pp. 147-153

Akhnoukh, A.K., (2010) “The effect of confinement on transfer and development length of 0.7-inch prestressing strands,” Proceedings of the 2010 Concrete Bridge Conference: Achieving Safe, Smart & Sustainable Bridges,” Phoenix, AZ

Ali, S., Naganathan, S., and Mahalingam, B., (2021), “State of the art review on prescriptive & performance-based approaches for concrete durability,” International Journal of Sustainable Construction Engineering and Technology, Vol. 12, No. 2, pp. 80-88

ASTM C1074-7 (2017). Standard Practice for estimating concrete strength by the maturity method, ASTM International, West Conshohocken, PA.

ASTM C143 / C143M-15a, (2015). Standard test method for slump of hydraulic-cement concrete, ASTM International, West Conshohocken, PA

ASTM C39 / C39M-18, Standard test method for compressive strength of cylindrical concrete specimens, ASTM International, West Conshohocken, PA, 2018

Beushausen, H., and Luco, F., (2016), “Performance-based specifications and control of concrete durability,” RILEM State-of-the-art Report.

Beushausen, H., Alexander, M.G., Basheer, M., Baroghel-Bouny, V., (2015), “Principles of the performance-based approach for concrete durability,” RILEM State-of-the-art Report

Elia, H., Ghosh, A., Akhnoukh, A.K., and Nima, Z.A., (2018), “Using nano- and micro- titanium dioxide (TiO2) in concrete to reduce air pollution,” Journal of Nanomedicine and Nanotechnology, Vol. (9), No. 3 DOI: 10.4172/2157-7439.1000505

Foliente (2000). Developments in performance-based building codes and standards,” Forest products Journal, Vol. (50), No. 7, pp. 12-21

U.S. Department of Transportation (2000). US 275, New concrete pavement, FHWA MCL Project #005, Valley, Nebraska

Lobo, C., Lemay, L., and Obla, K. (2006). Performance-based specifications for concrete, ASCE Architectural Engineering Conference (AEI), Nebraska, USA

Shah, S.P., Wang, K., and Weiss, W.J., (2000), “Is high strength concrete durable? Concrete technology for a sustainable development in the 21st century. E&FN Spon, 11 new Fetter lane, London, EC4P 4EE, U.K., ISBN: 0419250603

Ponding and Blisters – Study of SPF roofs

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Multiple roofing systems in the construction industry and installing high-quality roofing products are vital for efficient building operations. Inadequacies in design, materials, installation workmanship or maintenance can result in defects and surface anomalies in the roofing membrane-like blisters, open seams, and holes. The current study investigates if there is a relationship between roof distress features - blisters and ponding and the low slope sprayed polyurethane foam (SPF) roofs, especially when roofs do not conform to the minimum slope of 1/4 inch. The researchers' team conducted a quality inspection survey for the SPF roofs (#96 non-granular and #1068 granular aggregate roofs). The visual observations populated data to develop an account of the percentage of blisters and surface defects such as ponding, penetrations, delamination, and bird pecks of the SPF roofs. Statistical analyses utilizing Pearson correlation, t-test, and Chi-Square test evaluated the correlation between ponding and blisters to confirm if non-conforming roof slopes lead to defects and surface anomalies. As a result, the study established that the roof's slope significantly influenced the ponding area of granular and non-granular aggregate SPF roofs. Ponding and blisters are likely to exist in non-granular while ponding in granular roofs.
Key Words: ponding, blisters, SPF roof, granular aggregate roof, non-granular aggregate roof.

Introduction

The construction industry comprises multiple divisions: roofing, painting, mechanical, masonry, and electrical. Thermal and moisture protection, identification of quality issues, and compliance with quality standards are critical parameters for the ultimate product in all divisions (Gajjar et al., 2015). The roofing sector is critical, with the roof's function being the protection and shelter of the building from the weather (Kalamees et al., 2020; Guyer, 2018). There are multiple roofing systems in the construction industry, and installing high-quality roofing products is vital for efficient building operations (Gajjar et al., 2015). The single-ply roofing system is a system in which the principal roof covering is a single-layer flexible thermoset or thermoplastic membrane. In contrast, the multi-ply roofing system combines traditional materials such as felts and base sheet components. A built-up roof is a continuous, semi-flexible roof membrane consisting of multiple plies of saturated felts, coated felts, fabrics, or mats assembled in place with alternate layers of bitumen and surfaced with mineral aggregate, bituminous materials, a liquid-applied coating, or a granule-surfaced cap sheet (National Roofing Contractors Association, 2022; Guyer, 2018).

The focus of this study is to evaluate the distress features observed in roof types known as sprayed polyurethane foam (SPF). The SPF-based roof system is a composition of two components; the first is the rigid, closed-cell SPF insulation. SPF is a foamed plastic material formed by mixing and spraying two components—isocyanate ("A-component") and resin containing a polyol ("B-component") to form a rigid, fully adhered, water-resistant, insulating membrane (National Roofing Contractors

Association, 2022). The second component is the protective surface, typically a spray-applied elastomeric coating that can be applied using hand and power rollers (Gajjar et al., 2015). SPF is a lightweight, renewable roofing system with excellent insulating performance and can be installed over existing built-up roofing systems. However, the SPF roofing system's performance depends on the accurate and technically competent installation of the two-component system; thus, its performance depends on the contractor's expertise (Kashiwagi et al., 2002, 2016, 2017). 80% of building construction and facility problems pertain to roofing and waterproofing (Gajjar et al., 2014a). Previous research has indicated that inadequacy in design, materials, installation workmanship or maintenance can result in defects and surface anomalies in the roofing membrane-like blisters, open seams, and holes (Bailey & Bradford, 2005). Accumulating water on the roof of the building results in loads and deflections mutually dependent on each other, and the consequence is a non-linear effect known as ponding (Denavit, 2019). Penetration is a construction component (e.g., pipes, conduits, HVAC supports) that passes through a roof or waterproofing system (National Roofing Contractors Association, 2022). Not many studies utilize absolute metrics to measure the performance of a building or facility, and these common areas of measurement include cost, schedule, quality, and safety (Sharma et al., 2021). Quality and overall performance monitoring through regular data collection are critical and visual inspection is one of the methods to achieve it (Gajjar et al., 2014b, 2015). This paper analyzes a dataset of the visually recorded presence of blisters and ponding on low-slope SPF roofs across multiple projects. The study's objective is to evaluate and assess if there is any significant relationship between roof distress features like blisters and ponding with the roof's slope conforming to the minimum value of 1/4 inch.

The study's findings shall assist owners in developing and formulating efficient and effective maintenance plans for roofing systems in the facilities. The basis of the formulation of plans would be the study's findings pertinent to the correlation of the slope of the roofs. The research intends to assist the contractors in a comprehensive understanding of SPF roofs and the technical competence required for their successful and effective installation. The contractors will be further informed about the possible defects that will follow with poor workmanship in non-granular and granular aggregate roofs.

Methodology

Researchers conducted a quality inspection survey for the SPF roofs selected for this research. The observations of the visual inspection were recorded instantaneously, populating data to develop an account of the percentage of blisters and surface defects such as ponding, penetrations, delamination, and bird pecks of the SPF roofs. The following data points were measured in person and documented:

- Square footage of blisters
- Square footage of ponding
- Number of penetrations
- Square footage of delamination
- Square footage of bird pecks
- Slope of the roof (if the slope of the roof is less or more than 1/4")
- Type of roof: Non-Granular Aggregate Roof and Granular Aggregate Roof

The researchers conducted data analysis to study and evaluate the relationship between inspection observations: blisters, ponding with each other, and the roof's slope. Blisters and Ponding areas were studied in their absolute values and in categories of severity of Low, Medium (if applicable), and High by calculating the mean value and defining the limit of the severity. The analysis was structured in three phases delineated below:

1. Phase 1 – Evaluation of the impact of the roof's slope on the percentage of blisters and ponding on granular and non-granular aggregate roofs and study the relationship between the abovementioned parameters.
2. Phase 2 – Evaluation of difference in the area of blisters, ponding, and number of penetrations on the roof for two types of slopes of the non-granular aggregate roof
3. Phase 3 – Evaluation of difference in the area of blisters, ponding, and number of penetrations on the roof for two types of slopes of the granular aggregate roof.

Analyses, namely, Pearson correlation, t-test, and Chi-Square test, evaluated the correlation between ponding and blisters and corroborated if non-conforming roof slopes lead to defects and surface anomalies.

Analysis

A summary of the data captured in the survey is highlighted in Table 1 below. Table 1 reflects the averages of observations of areas of ponding and blisters. The measurements were recorded visually for non-granular aggregate and granular aggregate roofs for two conditions: when the roof's slope was less than 1/4" and when the roof's slope was not less than 1/4".

Table 1
Summary of Ponding and Blisters areas for types and slopes of the roof

	Non-Granular Aggregate Roof		**Granular Aggregate Roof**	
Areas (in sq.ft.)	**slope < 1/4”**	**slope not < 1/4”**	**slope < 1/4”**	**slope not < 1/4”**
No. of Samples	35	61	612	456
Ponding Mean	192	121	489	185
Blisters Mean	5	5	17	12
Total Ponding	6,716	7,410	29,9248	84,583
Total Blisters	190	326	10,622	5,577

Phase 1 Analysis: Non-Granular and Granular Aggregate Roofs

Blisters vs. Slope of Roof

Independent Samples T-test was conducted to assess the influence of the slope of the roof in the percentage area of blisters (in sq. ft.) on a sample database of non-granular and granular aggregate SPF roofs, and it was statistically insignificant. A chi-square test of independence examined the relationship between two categories of the area of blisters ("Low" if the percentage of blisters area was less than the average 0.0798% and "High" if the percentage of blisters area was more than the average 0.0798%) and the slope of the roof, and it was statistically insignificant.

Ponding vs. Slope of Roof

Independent Samples T-test was conducted to assess the difference in the percentage of the area of ponding between two types of roofs, roofs with a slope less than 1/4" and roofs with a slope not less than 1/4", and it was statistically insignificant. A chi-square test of independence examined the relationship between two categories of the area of ponding ("Low" if the percentage of ponding area was lower than the average 1.925% and "High" if the percentage of ponding area was more than the average 1.925%) and the slope of the roof, and it was statistically insignificant.

Phase 2 Analysis: Non-Granular Aggregate Roof

Blisters vs. Slope of Roof

To assess the impact of the two types of the slope, i.e., with a roof slope less than 1/4 inch and the other with a roof slope not less than 1/4 inch in the non-granular aggregate roof, on the area of blisters on the roof, an independent samples t-test was conducted using the square footage of "Blisters" as the dependent variable, and this difference was statistically insignificant. A chi-square test of independence examined the relationship between blisters on the non-granular aggregate roof (Low with an area less than equal to 5 sq. ft., High with an area greater than 5 sq. ft.), and slope of the roof - the relationship between these variables was statistically insignificant.

Blisters (Yes and No) vs. Slope of Roof: Chi-square Test. A chi-square test of independence examined the relationship between blisters on the non-granular aggregate roof (Yes if blisters are present and No if there are no blisters) and the slope of the roof (0 for the slope of roof not less than1/4", 1 or slope of the roof less than 1/4"). The relationship between these variables was statistically significant, $\chi 2$ (1, N = 100) = 5.983, $p < 0.05$ exhibiting a significant relationship between the presence of blisters on the non-granular aggregate roof and the roof's slope.

Table 2

Chi-Square test between "Slope of Roof" and "Blisters" in Non-Granular Aggregate Roof

	Value	df	Asymptotic Significance (2-sided)	Exact Sig. (2-sided)	Exact Sig. (2-sided)
Pearson Chi-Square	5.983	1	**.014***		
Fisher's Exact Test				.017	.012
N of Valid Cases	100				

** Significance for p < 0.05*

Ponding vs. Slope of Roof

To assess the impact of the two types of slopes in Non-Granular Aggregate Roofs, i.e., with a roof slope of less than 1/4 inch and the other with a roof slope not less than 1/4 inch on the area of Ponding on the roof, an independent samples t-test was conducted using the square footage of "Ponding" as the dependent variable - and this difference was statistically insignificant. A chi-square test of independence examined the relationship between ponding on non-granular aggregate roof (Low for ponding area less than 5 sq. ft., Medium for ponding area more than 5 sq. ft. and less than 100 sq. ft., High for ponding area more than 100 sq. ft.) and slope of roof - the relationship between these variables was statistically insignificant.

Ponding (Yes and No) vs. Slope of Roof: Chi-square Test. A chi-square test of independence examined the relationship between ponding on non-granular aggregate roof (Yes if ponding area is present and No if ponding area is absent) and slope of roof (0 for slope of roof not less than1/4", 1 or slope of roof less than 1/4"). The relationship between these variables was statistically significant, $\chi 2$ (1, N = 100) = 4.809, $p < 0.05$ exhibiting significant relationship between presence of ponding on non-granular aggregate roof and the slope of the roof.

Table 3

Chi-Square test between "Slope of Roof" and "Ponding" in Non-Granular Aggregate Roof

	Value	df	Asymptotic Significance (2-sided)	Exact Sig. (2-sided)	Exact Sig. (2-sided)
Pearson Chi-Square	4.809	1	**.028***		
Fisher's Exact Test				.033	.025
N of Valid Cases	100				

** Significance for $p < 0.05$*

Blisters vs. Ponding

Pearson's Correlation Test between Blisters and Ponding for Non-Granular Aggregate Roof with Slope less than 1/4 inch. To investigate whether the area of "Ponding" and "Blisters" were linearly related, a Pearson's correlation coefficient (r) between the two variables was calculated, $r = 0.796$, $n = 35$, $p < .001$. This result suggests that the area of "Ponding" in square footage and the area of "Blisters" in square footage were positively correlated. Specifically, as the area of "Ponding" increases, the area of "Blisters" tends to increase and vice versa.

Table 4

Correlation between "Ponding" and "Blisters" areas on Non-Granular Aggregate Roof with Slope less than ¼ inch

		Ponding Sq Ft	Blister Sq Ft
Ponding Sq Ft	Pearson Correlation	1	0.796**
	Sig. (2-tailed)		< 0.001
	N	35	35
Blister Sq Ft	Pearson Correlation	0.796	1
	Sig. (2-tailed)	**< 0.001****	
	N	35	35

*** Correlation is significant at the 0.01 level (2-tailed).*

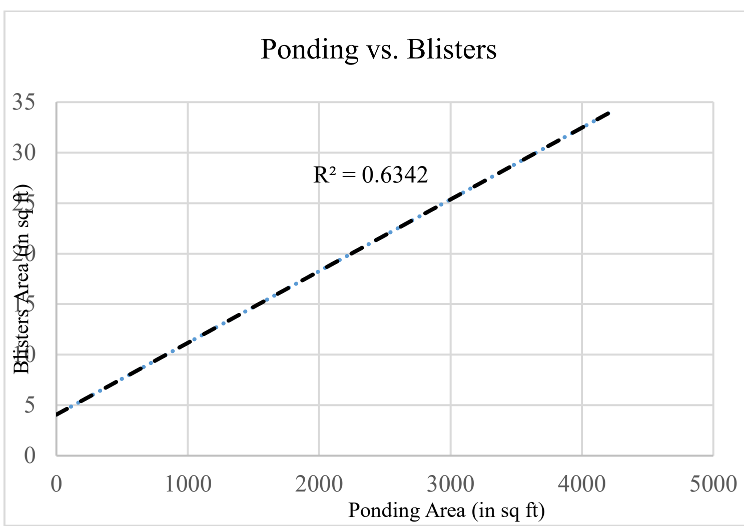

Figure 1. Correlation between ponding & blisters in non-granular aggregate roof (slope less than 1/4")

To investigate whether the area of "Blisters" and the area of "Ponding" were linearly related, a Pearson's correlation coefficient (r) between the two variables was calculated - the result was statistically insignificant. Hence a correlation could not be established between the area of "Blisters" and the area of "Ponding" for non-granular aggregate roofs.

Phase 3 Analysis: Granular Aggregate Roof

Blisters vs. Slope of Roof

To assess the impact of the two types of slopes, i.e. with roof slope less than 1/4 inch and the other with roof slope not less than 1/4 inch in granular aggregate roof, on the area of blisters on the roof, an independent samples t test was conducted using the square footage of "Blisters" as the dependent variable - and this difference was statistically insignificant. A chi-square test of independence examined the relationship between blisters on granular aggregate roof (Low with area less than equal to 15 sq. ft., High with area greater than 15 sq. ft.) and slope of roof. The relationship between these variables was statistically insignificant. A chi-square test of independence examined the relationship between blisters on granular aggregate roof (Yes if blisters are present and No if there are no blisters) and slope of roof. The relationship between these variables was statistically insignificant.

Ponding vs. Slope of Roof

Ponding vs. Slope of Roof: Independent Samples T-test. To assess the impact of the two types of slopes in Granular Aggregate Roofs, i.e., with a roof slope of less than ¼ inch and the other with a roof slope not less than ¼ inch on the area of Ponding on the roof, an independent samples t-test was conducted using the square footage of "Ponding" as the dependent variable. The average impact for a roof with a slope less than ¼ inch ($M = 488.97$, $SD = 2450.97$) was greater than that of a roof with a slope not less than ¼ inch ($M = 185.48$, $SD = 1403.81$), and this difference was statistically significant, $t(1005.674) = .011$, $p < 0.05$. The 95% confidence interval for the mean difference was (-536.808, -70.164). Overall, it can be deduced that ponding area is higher in granular aggregate roofs with slope less than 1/4 inch.

Table 5
Group Statistics for Independent Samples T-test for "ponding" in granular aggregate roof for two types of slopes

	Slope of Roof	N	Mean	Standard Deviation	Standard Error Mean
Ponding Sq Ft	Slope not less than 1/4"	456	185.48	1403.805	65.739
	Slope less than 1/4"	612	488.97	2450.971	99.075

Table 6
Independent Samples T-test for "ponding" in granular aggregate roof for two types of slopes

		t	df	Two-Sided p	Mean Difference
Ponding Sq Ft	Equal Variances not assumed	-2.552	1005.674	**.011***	-303.486

** Significance for p < 0.05*

Ponding (Low and High) vs. Slope of Roof: Chi-square Test. A chi-square test of independence examined the relationship between ponding on granular aggregate roof (Low for ponding area less than 359 sq. ft., High for ponding area more than 359 sq. ft.) and slope of roof (0 for slope of roof not less than1/4", 1 or slope of roof less than 1/4"). The relationship between these variables was statistically significant, $\chi 2$ (1, N = 1068) = 30.463, $p < .001$. Results show that ponding is more likely to be present in granular aggregate roofs with slope less than 1/4 inch.

Table 7
Chi-Square test between "Slope of Roof" and "Ponding" in Granular Aggregate Roof

	Value	df	Asymptotic Significance (2-sided)	Exact Sig. (2-sided)	Exact Sig. (2-sided)
Pearson Chi-Square	30.463	1	**< .001****		
Fisher's Exact Test				< .001**	< .001**
N of Valid Cases	1068				

** *Significance for p < 0.001*

Ponding (Yes and No) vs. Slope of Roof: Chi-square Test. A chi-square test of independence examined the relationship between ponding on a granular aggregate roof (Yes if ponding area is present and No if ponding area is absent) and slope of the roof (0 for the slope of roof not less than1/4", 1 or slope of the roof less than 1/4"). The relationship between these variables was statistically significant, $\chi 2$ (1, N = 1068) = 25.675, $p < 0.001$ exhibiting a significant relationship between ponding on the granular aggregate roof and the roof's slope.

Table 8
Chi-Square test between "Slope of Roof" and "Ponding" in Granular Aggregate Roof

	Value	df	Asymptotic Significance (2-sided)	Exact Sig. (2-sided)	Exact Sig. (2-sided)
Pearson Chi-Square	25.675	1	**< .001****		
Fisher's Exact Test				< .001**	< .001**
N of Valid Cases	1068				

** *Significance for p < 0.001*

Blisters vs. Ponding

To investigate whether the area of "Ponding" and "Blisters" were linearly related for Granular Aggregate roofs with slope less than 1/4 inch, a Pearson's correlation coefficient (r) between the two variables was calculated - the result was statistically insignificant. To investigate whether the area of "Ponding" and "Blisters" were linearly related for Granular Aggregate roofs with slope not less than 1/4 inch, a Pearson's correlation coefficient (r) between the two variables was calculated - the result was statistically insignificant. Thus, a correlation could not be established between the area of "Blisters" and the area of "Ponding" for granular aggregate roofs.

Results

The findings from the analyses that exhibited statistically significant results in the three phases are tabulated in Table 9 below.

Table 9
Statistically significant results from Phase I, II, and III analyses

Type of Roof	Independent Variable	Dependent Variable	Statistical Analysis	p-value
Non-granular aggregate roof	Slope of Roof	Yes vs. No for Blisters	Chi-Square	.014*
		Yes vs. No for Ponding	Chi-Square	.028*
Non-Granular Aggregate Roof with Slope < ¼"	Ponding Sq ft and Blisters Sq ft		Pearson's Correlation	< .001**
Granular Aggregate Roof	Slope of Roof	Ponding Sq. ft.	t-test	.011*
	Slope of Roof	Low vs. High Area of Ponding Sq. ft.	Chi-Square	< .001**
	Slope of Roof	Yes vs. No for Ponding	Chi-Square	< .001**

* *Significance for* $p < 0.05$
** *Significance for* $p < 0.001$

Discussion

The results obtained from the data analysis conducted for the sample of roofing inspection data indicate significant findings for the roofing industry:

1. In non-granular aggregate roofs, there is a higher probability of blisters and ponding for roofs with slopes less than 1/4 inch.
2. In non-granular aggregate roofs, there is a strong correlation between ponding and blisters in roofs with slopes less than 1/4 inch. The result also indicates that approximately 63% of the variance is shared between ponding and blisters for non-granular aggregate roofs with slopes less than 1/4 inch. The two parameters are also directly related to each other, which implies that as the area of ponding increases, the area of blisters also increases and vice versa.
3. Phase 3 Analysis deduced that the slope of the granular aggregate roof has a more substantial impact on the ponding area recorded; however, there was no significant relationship between the presence of blisters on the granular aggregate roof and the slope of the roof.

The study's findings showed that the roof's slope significantly influenced the ponding area of the granular aggregate roofs. There was also a significant correlation between the "low" and "high" percentage of ponding areas and the roof's slope. Reinforcing this, the correlation between the presence of ponding and the slope of the roof was also significant. However, the data analysis could establish no significant relationship between blisters and ponding for granular aggregate roofs.

Conclusion

This study intends to highlight the relationship between roof distress parameters, namely, blisters and ponding, and evaluate the presence and coverage on roofs with the roof's slope. The data analysis findings show that the roof's slope significantly impacts the ponding area recorded in granular aggregate roofs. On the contrary, there was no significant relationship between blisters and the roof slope for the granular aggregate roof. However, in non-granular aggregate roofs, a strong correlation was observed between blisters and ponding. The significant relationship exhibits that since blisters are primarily a consequence of application/installation shortcomings (Gajjar et al., 2015), contractors are recommended to ensure the accurate, technically adequate installation of SPF roofs for non-granular aggregate type to avoid ponding. There is an opportunity to study the presence of blisters and ponding across different regions using the same dataset for roofing projects to assess if a relationship exists between roof exposure to different climatic conditions. The study can be extended for the evaluation of the influence of different seasons and temperatures on the presence of ponding and blisters on the roof. Also, future scope for research exists in studying the presence of blisters and ponding vis-a-vis the roof's age. Evaluation of the number of penetrations corresponding to the roof's age can also be a future research focus.

References

Bailey, D. M., & Bradford, D. (2005). Membrane and Flashing Defects in Low-Slope Roofing : Causes and Effects on Performance. *ASCE JOURNAL OF PERFORMANCE OF CONSTRUCTED FACILITIES*, *19*(August), 234–243. https://doi.org/10.1061/(ASCE)0887-3828(2005)19

Denavit, M. D. (2019). Approximate ponding analysis by amplified first-order analysis. *Engineering Structures*, *197*(July). https://doi.org/10.1016/j.engstruct.2019.109428

Gajjar, D., Kashiwagi, D., Kashiwagi, J., & Sullivan, K. (2014a). Best Value Case Study for Cold Storage Facility in Miami, Florida. *Journal for the Advancement of Performance Information and Value*, *6*(1), 53. https://doi.org/10.37265/japiv.v6i1.71

Gajjar, D., Kashiwagi, J., Kashiwagi, D., & Sullivan, K. (2014b). Maintaining the Quality of Constructed Facilities Using the Performance Information Measurement System: A Three-Year Study on SPF Roofing. International Journal of Facility Management, 5(2).

Gajjar, D., Kashiwagi, D. T., Sullivan, K. T., & Kashiwagi, J. (2015). Postoccupancy Performance Evaluation of Time-of-Installation Factors: Seven-Year Study of SPF Roofing. *Journal of Performance of Constructed Facilities*, *29*(2), 1–8. https://doi.org/10.1061/(asce)cf.1943-5509.0000500

Guyer, J. P., & PE, R. (Eds.). (2018). An Introduction to Roofing Systems. Guyer Partners.

Kalamees, T., Ilomets, S., Põldaru, M., Klõseiko, P., Kallavus, U., Rosenberg, M., & Õiger, K. (2020). Analysis of causes of the end of service life of a spray polyurethane foam and polyurea roof. *E3S Web of Conferences*, *15002*(172), 1–6. https://doi.org/http://doi.org/10.1051/e3sconf/20201721 0502

Kashiwagi, D. T., & Tisthammer, T. (2002). Information based delivery system for sprayed polyurethane foam in roofing. Journal of Thermal Envelope and Building Science, 26(1), 33-52.

Kashiwagi, D., Zulanas IV, C., & Gajjar, D. (2016). The Cost Effectiveness of Alpha SPF Roofs: Casa View Elementary School Roofing Case Study. Journal for the Advancement of Performance Information and Value, 8(2), 42-57.

Kashiwagi, D. T., Zulanas, C., & Gajjar, D. (2017). The Value of Alpha SPF Roofing: An Alpha Case Study at William Lipscomb Elementary School. *Journal for the Advancement of Performance Information and Value*, *9*(2), 21–48. https://doi.org/10.1044/leader.ppl.22122017.24

National Roofing Contractors Association. (n.d.). *www.nrca.net*. Retrieved October 19, 2022, from https://www.nrca.net/

Sharma, V., Caldas, C. H., & Mulva, S. P. (2021). Development of metrics and an external benchmarking program for healthcare facilities. *International Journal of Construction Management*, *21*(6), 615–630. https://doi.org/10.1080/15623599.2019.1573490

Mental Health and Well-being in the Irish Construction Industry: A Preliminary Investigation into the Main Stressors

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The construction industry is renowned as being masculine and competitive, due to its male-dominated and cutthroat nature, where mental health is often disregarded. Thankfully, in recent times, workers' mental health has started to become a priority to upper management, however, problems still exist. Therefore, this study aims to determine what are the main stressors leading to poor mental health, and what strategies can be implemented to tackle the issue, in the Irish construction industry. A mixed methods approach was undertaken, using five semi-structured individual interviews, and a questionnaire survey with professionals working in the Irish construction industry. The data was thematically analysed where emerging themes and topics were identified. Four main stressors were identified: long work and commute hours, poor work-life balance, unrealistic work goals and overload, and the 'macho man' culture and stigma preventing workers from speaking out. Three key strategies were identified: mental health training within the organisation, communication of clear work goals and objectives, and reduction of work hours and remote / flexible working. Overall, the key contribution of this study emphasises that there are many stressors leading to poor mental health, however, key strategies can be incorporated to counteract these issues across the Irish construction industry.

Key Words: Culture, Ireland, Mental Health, Welfare, Well-being.

Introduction

Mental health problems in the construction industry are significantly higher than in many other industries (Clarke et al., 2020), which Sanderson (2017) argues is due to its masculine culture. Carson and Davies (2019) support that the industry is notoriously conservative, male-dominated and emphasizes performance under pressure due to its competitive and demanding nature. These characteristics can affect employees' day to day lives in various ways, as different roles across the construction sector can bring different stressors such as long working hours and travel times to work, high production pressures and stigma associated with these roles. The Chartered Institute of Building

(CIOB) found that 26% of construction industry professionals thought about taking their own lives in 2019, before the COVID-19 pandemic had hit the industry, and 97% admitted to being stressed at least once in the last year (CIOB, 2020). With the pandemic providing uncertainty over job security, isolation, and tight project deadlines, this can be devastating to the construction industry and to the mental health of employees. Gayed (2019) corroborates that when not adequately addressed, work-related mental health factors can result in substantial costs to the individual, their workplace, and to the economy. Clarke et al. (2020) found that there are mental health initiatives in place in the UK (Mates in Mind), Australia (Mates in Construction), and more recently in Ireland (Mind our Workers). However, the literature identifies that further gaps exist within the Irish context, thus, more research is necessary. Therefore, the aim of this study is to determine what are the main stressors leading to poor mental health, and what strategies can be implemented to tackle the issue, in the Irish construction industry.

Mental Health in the Construction Industry

The Advisory, Conciliation and Arbitration Service (ACAS, 2019) define mental health as our state of 'emotional, psychological and social well-being; it affects how we think, feel and act'. In the UK, the Health and Safety Executive (HSE, 2020) found that anxiety and depression have overtaken musculoskeletal issues as the most reported health problem in the construction sector; with 454 construction workers dying by suicide in 2016 (CIOB, 2019). Deaths caused by accidents on site have decreased from 200 to 40 in the past 60 years however, the number of suicides, caused by mental health problems, including depression, stress, and anxiety, has been passive at approximately 280 per annum (Sanderson, 2017).

The Office for National Statistics (ONS, 2017) states that construction workers are six times more likely to die from suicide than a fall from a height. However, despite significant improvements in the safety of the construction workforce in recent times, mental health has become a silent deadlock. Leung et al. (2008) and Love et al. (2010) found that the mental health of the construction workforce has been linked to excessive job demands and low levels of control and support', and Ireland tends to lag other countries in comparison with support systems and frameworks.

Stigma

According to Link and Phelan (2001), stigma can be referred to as the process of labelling, stereotyping, and separating groups leading to status loss and bigotry toward specific group members. Additionally, stigma may occur if individuals with mental illness endorse stereotypes about themselves, anticipate possible negative social repercussions, and believe that they are tainted members of the community (Livingston and Boyd, 2010). Men suffer from the stigma around mental health, and O'Brien et al. (2005) found that men are routinely less likely to seek help for health issues because of shame and stigma attached to masculinity. Clarke et al., (2020) concur that men generally feel uncomfortable talking about their feelings, keep their emotions under wraps and tend to put their head down and carry on with their work.

Men are commonly less mindful of mental health problems (Cotton et al., 2006), and the social stigma attached to mental ill-health is preventing employees from seeking help early on, due to feelings of weakness and shame (CIOB, 2020). Alderson (2017) supports that most male workers do not seek mental health support from their employer due to shame. In male-dominated industries such as construction, achieving masculinity channels workers to believe enduring pain and camouflaging mental health issues is necessary, to display toughness, and self-dependence, and prove their valuation and reliability (Wong et al., 2017). Furthermore, Stergiou-Kita et al. (2015) argue that men are inspired to perform in conformity with masculine traits such as courage, obtaining risks and enduring mental and physical pain without grievance.

Stressors

Lingard and Turner (2015) believe that construction work is defined by high demands and low levels of workers' health control, which contributes to workers' mental health problems. For instance, one-quarter of the construction workers in the UK have contemplated suicide; 90% of construction workers who have contemplated suicide or have known someone who committed suicide, did not seek support (Alderson, 2017). Love et al. (2010) found that the most momentous stressors highlighted were work overload, role ambiguity and conflict, unpaid overtime, restrictive career progression, the diverse range of personalities encountered in the work environment, redundancy, client demands, limited resources, financial pressures, budget constraints, and solving trivial but pressing and irksome problems.

Alavinia et al. (2007) discovered work-related circumstances such as high work demands, job pressure, a lack of support at work and low levels of job control to be significantly impacting workers' health. In Ireland, a study by the Construction Industry Federation (CIF, 2020) across 1,266 companies found that 70% of employers indicate poor mental health in the construction sector due to work-related issues. The primary work-related reasons causing poor mental health in the construction industry included general work-related stress (44%), unrealistic work goals at (29%), lengthy working hours at (22%), a macho work culture where employees are uncomfortable seeking help (16%), bullying culture (15%), and poor communication between management line and staff (9%). A Eurostat report (2007) found that 30% of European workers highlighted that their mental well-being was affected by psychosocial risks, which was most commonly a poor work-life balance.

Research Method

This study is part of a preliminary investigation which aims to contribute to both industry and academia. Considering the theoretical stance and reasoning this research is founded on, a critical realism approach is adopted, as Wikgren (2004) argues that critical realists maintain that one should move from providing a prediction to an explanation through investigation. Also, the ontological approach is that of a subjectivist, as the nature of the study mainly concerns the opinions of human participants (Curran et al., 2018).

Participant	Title	Company	Experience
A	Managing Director	Charity addressing the stigma of poor mental health in the construction industry (UK)	25 Years
B	Health, Safety & Wellbeing Officer	Large Construction Housing Developer (Ireland)	6 Years
C	Quality, Health & Safety Manager	Construction Supplier (Ireland)	10 Years
D	Site Engineer	Large Main Contractor (Ireland)	10 Years
E	Tradesman	Subcontractor (Ireland)	8 Years

Table 1. Interview Participants Demographic Information

A mixed methods research approach is utilised, encompassing both qualitative and quantitative techniques including an informative literature review, five semi-structured individual interviews and a questionnaire survey. Clarke-Hagan et al. (2018) argue that adopting a pluralistic approach such as mixed methods will be rewarded with, triangulated, validated and reliable results. A semi-structured interview format is chosen as it determines people's subjective reactions to situations, thus, extending the researcher's knowledge on the topic (McIntosh and Morse 2015). Details of the interviewees is included in Table 1. From an ethical perspective, the participants were informed of the nature of the research, its purpose and what the resultant data was used for, prior to commencement of interviews. Also, the identities of those involved remained anonymous and confidential information is not disclosed. Questionnaires are also a widely used means of collecting data, and it is an easy way to get responses from many people (Rowley 2014).

Findings and Analysis

The individual interviews began by obtaining generic background information from each participant. This was followed by a comprehensive conversation on mental health in the construction industry. This involved identifying the main stressors leading to poor mental health in the Irish construction industry, how it affects employee's productivity in the workplace and what strategies could be implemented to reduce these stressors, as well as discussing how the stigma around mental health prevents workers from speaking out. A semi-structured interview process was used to firstly answer original questions but allowed them to highlight any points they thought were necessary to examine further.

Findings from the interviews were analysed and summarized using thematic analysis. Thematic analysis is a method of analyzing, identifying, and reporting themes or patterns within data (Braun & Clarke, 2006). Thematic analysis can be used to analyse face-to-face data collection such as interviews (Terry, et al. 2017). The interviews were analysed by establishing themes found in the interview transcripts, including topics for discussion and keywords. Due to space limitations, only results from the qualitative analysis have been displayed in Tables 2 and 3, however, the quantitative analysis results are discussed in the next section.

Main Stressors Leading to Poor Mental Health	Participant A	Participant B	Participant C	Participant D	Participant E
Macho Man Culture	x	x	x	x	x
Stigma	x	x	x	x	x
Unrealistic Project Deadlines		x		x	x
Insufficient Work Funds / Resources	x	x			x
Long Work and Commute hours		x	x	x	
Work-Life Balance	x	x	x	x	
Work Overload – Clear Goals and Objectives not set out		x		x	
Boom / Bust Industry – Job Security	x	x	x	x	
Alcohol / Drug Abuse	x				x
Negative Coworker Relationships				x	

Table 2. Main Stressors Identified from the Individual Interviews

Out of ten stressors identified in Table 2, the five most common across the five interviews included 'Macho Man Culture', 'Stigma', 'Work-Life Balance', 'Boom / Bust Industry – Job Security' and 'Long Work and Commute Hours'.

Main Strategies to Reduce the Stressors	Participant A	Participant B	Participant C	Participant D	Participant E
Mental Health Training and Support within the Organisation	x	x	x	x	
Communication of Clear Work Goals		x		x	x
Remote / Flexible Working	x	x	x	x	
Reduction of Work Hours	x	x		x	x
Mental Health Champions / First Aiders	x				
Delegating Work				x	
Teambuilding Events		x			x

Table 3. Main Strategies Identified from the Individual Interviews

Out of seven strategies identified in Table 3, the five most common across the five interviews included 'Mental Health Training and Support within the Organisation', 'Remote / Flexible Working', 'Reduction of Work Hours', 'Communication of Clear Work Goals', and 'Teambuilding Events'.

The overall layout of the questionnaire survey was designed in a simple and clear format, to ensure clarity and to encourage a high response rate. Twenty-one questions were included in total, broken down into four key sections: demographics and profiling, stressors, strategies and two open-ended summary questions to conclude. The wording of each question was written in a short, precise and simple manner, avoiding bias and vagueness (Dillman and Smyth, 2007), and the two main sections, stressors and strategies, were close-ended questions, where participants answers were defined to a firm set of responses (Roopa and Rani, 2012). Using a convenience sampling strategy (Robinson, 2014), the survey was distributed across five large contracting construction companies around the Dublin region, utilizing the researcher's own industry contacts. The survey was accessible to approximately five hundred people, ranging from senior management to subcontracting employees. One-hundred-and-eight responses were returned, resulting in a response rate of 22%. This return rate appeared quite low; however, this response rate is not unusual for a construction industry survey, as Akintoye (2000) states that for most questionnaire surveys in construction, the normal response rate is 20-30%.

Discussion

Stressors Leading to Poor Mental Health

Long Work and Commute Hours: The survey results revealed that long working and commute hours were the most popular choice (48%), supporting the CIF (2020) in Ireland where 22% found that lengthy working hours was the main cause of poor mental health. Also, three of the five interviewees discussed how long commutes to work were an issue. Participant B, a Health, Safety and Wellbeing Officer noted, 'It can take up to 2 hours for workers to travel on-site, be in for 7am and leave at 5.30pm, by the time they are home they are physically and mentally exhausted'.

Work-Life Balance: The study found that only 47% of respondents either strongly agreed or agreed that they had an acceptable work-life balance. Quinlan (2020) identified that only 30% of people believe they have a good work-life balance. Also, 60% experienced stress or anxiety at least once a week over spending too little time with their families. Four out of the five interviewees supported that a poor work-life balance had a negative impact on their personal family lives. Participant A, the Managing Director of the Mental Health Charity lamented, 'You have got the uncertainty of working away from home, away from loved ones and the circumstances being out of your control'.

Unrealistic Work Goals and Overload: The survey found that 82% of the participants had unrealistic targets and work goals, and Love et al. (2010) found the most momentous stressor highlighted in their study was work overload. Two of the five interviewees discussed at length how clear goals and objectives were sometimes not set out correctly, which resulted in a huge work overload. Participant E, a Tradesman with a Subcontracting Company concurred, 'I have noticed a huge overload of work, especially on big sites where managers or foremen want me to be everywhere at once instead of having a set daily routine'.

Macho Man Culture: In the questionnaire survey, 56% of the participants identified macho man culture as one of the key stressors in the industry. Sanderson (2017) noted that the reason for poor mental health among construction workers and their denial to seek help is due to the masculine culture of the construction industry. All five of the interviewees believed the stigma and macho man culture within the construction industry are preventing workers from speaking out. Participant C, the Quality, Health and Safety Manager stated, 'The sheer number of men on these sites brings the element of a 'macho man' culture as they don't want to be seen as vulnerable to others'. Furthermore, Participant B, the Health, Safety and Wellbeing Officer added that it is more prevalent among the site workers rather than the management team. O'Brien et al. (2005) support that men are routinely less likely to seek help for health issues because of the shame and stigma attached to masculinity.

Strategies to Counteract the Stressors

Mental Health Training Within the Organisation: Four out of the five interviewees agreed that mental health training in the workplace was paramount. Similarly, 81% of the survey respondents identified training as a key strategy. Training within organisations can be seen to be lacking when looking at the CIOB (2019) survey, where it was found that 71% of people haven't received formal mental health training in the past three years. Participant B, the Health, Safety and Wellbeing Officer suggested that as part of the safe pass course, mental health training could be incorporated into its design. Participant D, a Site Engineer with a Large Main Contractor had a positive experience, stating, 'The company I am working with are great for awareness around men's mental health and well-being, we have different types of training and workshops throughout the year which help with awareness around the subject. As these training and events highlight just how many men suffer in silence, it helps reduce the stressors as you know you aren't the only person feeling this way'.

Communication of Clear Work Goals and Objectives: Of the one-hundred-and-eight survey respondents, 84% had communication selected. Supporting this, three of the five interviewees noted clear work goals as a key strategy to help reduce stress and mental health problems. Campbell and Gunning's (2020) study corroborates this finding as 33% of respondents thought management did not consider their current well-being when distributing workloads, leading to an increased risk of mental health problems. The interviewees highlighted the need for clear work instructions and goals as a key strategy to reduce stress and poor mental health. Participant E, the Site Engineer, suggested 'This should be done on a regular basis during the project, but also clearly defined goals set out prior to the project starting. The management should meet and delegate appropriate duties and assign them to employees, with each member having individual roles and responsibilities'.

Reduction of Work Hours and Remote / Flexible Working: Reduction in work hours was selected by 52% of survey participants in their top five strategies, and this was supported by four out of the five interviewees. Overall, they noted that a reduction in work hours would be a key strategy for improving workers' mental health and stress. Wildes (2005) agrees that long work hours negatively impact workers' mental health. Participant E, the Tradesman highlighted, 'I think the work hours could be reduced as most lads spend a huge amount of time in work and also travelling to and from it'. Montreuil and Lippel (2003) found that flexible working led to fewer stress levels for workers due to them having more control of their life. Participant D, the Site Engineer agreed, 'I noticed that during the Covid pandemic that remote working where possible was a great strategy to reduce stress'. George et al. (2022) established that one of the lessons learnt from the Covid-19 pandemic is that remote working results in reduced stress and better overall health and quality of life.

Conclusion and Recommendations

Essentially, this preliminary study focuses on poor mental health and the main stressors among the construction workforce in Ireland. The safety of the construction workforce has thankfully received great attention in recent times; however, the mental health and well-being of all construction workers remains a cause for concern. Nevertheless, despite the stigma surrounding this sensitive area, positive strides have been made in the industry. Considering the results captured from the five individual interviews and one-hundred-and-eight questionnaire responses in this research, four key themed stressors emerged, including Long Work and Commute Hours, Work-Life Balance, Unrealistic Work Goals and Overload, and a Macho Man Culture. When analyzing these influencing stressors, counteractive strategies also emerged, including Mental Health Training Within the Organisation, Communication of Clear Work Goals and Objectives, and Reduction of Work Hours and Remote / Flexible Working.

However, the findings from the individual interviews and questionnaire surveys are specific to this research; and only a concise, subjective view of the topic is produced, thus, not a generalized view. Nonetheless, this study provides a solid foundation to advance and explore further, supporting continuous research into the mental health of workers on construction projects in Ireland. The findings in this study can be developed further, and it is anticipated that a broader analytical context can be addressed in a subsequent journal publication, where additional theoretical points of departure and areas of discussion can be articulated. It is proposed that further studies consider the contribution that training bodies and educational institutions can make to the current and emerging workforce, to encourage and promote positive mental health and well-being.

To gain a richer understanding of the topic, alternative qualitative research methods can be implemented in further research such as action research and ethnography. It is recommended that more individual interviews and focus groups seminars are considered for qualitative analysis, and a sequential selection strategy is incorporated using criterion selection, such as quota and random sampling. From a quantitative perspective, a questionnaire survey could be composed and distributed to a larger sample across other regions of Ireland to further strengthen the research. Still, this study provides a foundation for informing and confirming the validity and necessity of the research and ensuing investigation going forward. Overall, the key contribution of this study emphasizes that there are many stressors leading to poor mental health, however, key strategies can be incorporated to counteract these issues across the Irish construction industry.

References

Advisory, Conciliation and Arbitration Service (ACAS), (2019), 'Promoting Positive Mental Health in the Workplace', available at: https://www.acas.org.uk/supporting-mental-health-workplace (Accessed October 2022)

Akintoye, A., (2000), 'Analysis of factors influencing project cost estimating practice', *Construction Management & Economics*, 18(1), pp. 77-89.

Alavinia, S.M., van Duivenbooden, C. and Burdorf, A., (2007), 'Influence of work-related factors and individual characteristics on work ability among Dutch construction workers', *Scandinavian journal of work, environment & health*, pp.351-357.

Alderson, L., (2017), 'Uncovered: The truth behind construction's mental health', Construction News, available at: https://www.constructionnews.co.uk/10019419 (Accessed October 2022)

Braun, V. and Clarke, V., (2006), 'Using thematic analysis in psychology', *Qualitative research in psychology*, 3(2), pp.77-101.

Campbell, M.A. and Gunning, J.G., (2020). 'Strategies to improve mental health and well-being within the UK construction industry. *Proceedings of the Institution of Civil Engineers Management, Procurement and Law*, 173(2), pp.64-74

Carson, V. and Davies, K., (2019), 'Managing company responsibility for mental health in the New Zealand construction industry', in: CIB World Building Congress 2019, 17-21 June, Hong Kong, China.

Chartered Institute of Building (CIOB), (2019), 'Starting the conversation about mental health in the construction industry', available at: https://www.ciob.org/blog/starting-conversation-about-mental-health-construction-industry (Accessed October 2022)

Chartered Institute of Building (CIOB), (2020), 'Understanding Mental Health in the Built Environment', available at: https://www.ciob.org/industry/research/Understanding-Mental-Health-Built-Environment (Accessed October 2022)

Clarke, N., Bradley, J.G. and Spillane, J.P., 2020, September. Mental health and well-being in micro enterprises in the construction industry: an Irish perspective. In Proceedings of the 36th annual ARCOM conference (pp. 7-8).

Clarke-Hagan, D., Spillane, J. and Curran, M., (2018), 'Mixed Methods Research: A Methodology in Social Sciences Research for the Construction Manager', in proceedings of annual RICS COBRA Conference, 23-24 April 2018, London, England, Royal Institute of Chartered Surveyors

Construction Industry Federation (CIF), (2020), 'Mental Health in the Construction Sector', p.14., available at: https://cif.ie/wp-content/uploads/2020/09/1237-CIF-Mental-Health-Report-LR.pdf (Accessed October 2022)

Cotton, S.M., Wright, A., Harris, M.G., Jorm, A.F. and McGorry, P.D., (2006), 'Influence of gender on mental health literacy in young Australians', *Australian & New Zealand Journal of Psychiatry*, 40(9), pp.790-796.

Curran, M., Spillane., J. and Clarke-Hagan, D., (2018), 'External Stakeholders in Urban Construction Development Projects: Who Are They and How Are They Engaged?', in: Gorse, C. and Neilson, C.J. (Eds.), proceedings of the 34th Annual ARCOM Conference, 3-5 September 2018, Belfast, UK, Association of Researchers in Construction Management, pp. 139-148

Dillman, D.A. and Smyth, J.D., (2007), 'Design effects in the transition to web-based surveys', *American Journal of Preventive Medicine*, 32(5), pp. S90-S96.

Eurostat, (2007), 'European union labour force survey', Eurostat: Luxembourg.

Gayed, A., Tan, L., LaMontagne, A.D., Milner, A., Deady, M., Milligan-Saville, J.S., Madan, I., Calvo, R.A., Christensen, H., Mykletun, A. and Glozier, N., (2019), 'A comparison of face-to-face and online training in improving managers' confidence to support the mental health of workers’, *Internet interventions*, 18, p.100258.

George, T.J., Atwater, L.E., Maneethai, D. and Madera, J.M., (2022), ‘Supporting the productivity and wellbeing of remote workers: Lessons from COVID-19’, *Organizational Dynamics*, 51(2).

Health and Safety Executive (HSE), (2020), ‘Work-related stress, anxiety or depression statistics in Great Britain’, available at: https://www.hse.gov.uk/statistics/causdis/stress.pdf (Accessed October 2022)

Leung, M.Y., Chan, Y.S. and Olomolaiye, P., (2008), ‘Impact of stress on the performance of construction project managers’, *Journal of construction engineering and management*, 134(8), pp.644-652.

Lingard, H. and Turner, M., (2015) ‘Improving the health of male, blue collar construction workers: a social ecological perspective’, *Construction management and economics*, 33(1), pp.18-34.

Link, B.G. and Phelan, J.C., (2001), Conceptualizing stigma. *Annual review of Sociology*, 27(1), pp.363-385.

Livingston, J.D. and Boyd, J.E., (2010), ‘Correlates and consequences of internalized stigma for people living with mental illness: A systematic review and meta-analysis’, *Social science & medicine*, 71(12), pp.2150-2161.

Love, P.E., Edwards, D.J. and Irani, Z., (2010), ‘Work stress, support, and mental health in construction’ *Journal of construction engineering and management*, 136(6), pp.650-658.

McIntosh, M.J. and Morse, J.M., (2015), ‘Situating and constructing diversity in semi-structured Interviews’, *Global Qualitative Nursing Research*, 2, 1-10.

Montreuil, S. and Lippel, K., (2003), Telework and occupational health: a Quebec empirical study and regulatory implications. *Safety Science*, 41(4), pp.339-358.

O’Brien, R., Hunt, K. and Hart, G., (2005), ‘It's caveman stuff, but that is to a certain extent how guys still operate’: men's accounts of masculinity and help seeking. *Social science & medicine*, 61(3), pp.503-516.

Office for National Statistics (ONS), (2017), ‘Sickness absence in the labour market’, Newport.

Quinlan, A., (2020), ‘Study finds 70% of employees experiencing stress at work’, The Irish Times.

Robinson, O.C., (2014), ‘Sampling in interview-based qualitative research: A theoretical and practical guide’, *Qualitative research in psychology*, 11(1), pp. 25-41.

Roopa, S. and Rani, M.S., (2012), ‘Questionnaire designing for a survey’, *Journal of Indian Orthodontic Society*, 46(4_suppl1), pp.273-277.

Rowley, J., (2014), Designing and using research questionnaires, *Management Research Review*, 37(3), pp. 308-330.

Sanderson, R., (2017), ‘Mental health focus: what is the construction industry helpline?’, available at: https://www.shponline.co.uk/safety-management/what-is-the-construction-industry-helpline-bill-hill-explains/ (Accessed October 2022)

Stergiou-Kita, M., Mansfield, E., Bezo, R., Colantonio, A., Garritano, E., Lafrance, M., Lewko, J., Mantis, S., Moody, J., Power, N. and Theberge, N., (2015). Danger zone: Men, masculinity and occupational health and safety in high-risk occupations. *Safety science*, 80, pp.213-220.

Terry, G., Hayfield, N., Clarke, V. and Braun, V., (2017), Thematic analysis. The SAGE handbook of qualitative research in psychology, 2, pp.17-37.

Wikgren, M., (2004), 'Critical realism as a philosophy and social theory in information science?', *Journal of Documentation*, 61(1), pp.11-22.

Wildes, V.J., (2005), ‘Stigma in food service work: How it affects restaurant servers' intention to stay in the business or recommend a job to another’, *Tourism and Hospitality Research*, 5(3), pp.213-233

Wong, Y.J., Ho, M.H.R., Wang, S.Y. and Miller, I.S., (2017), ‘Meta-analyses of the relationship between conformity to masculine norms and mental health-related outcomes’, *Journal of counselling psychology*, 64(1), p.80.

Environmental Benefits of Using Activated Sugarcane Bagasse Ash in Cementitious Materials.

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In this research, a comprehensive environmental-based approach is applied to evaluate the effectiveness of biomass ashes processing methods to produce cementitious materials. Efforts are put in research to obtain new low-carbon cementitious materials by incorporating waste, such as sugarcane bagasse ash (SCBA). Processing methods are commonly used to counteract the drawbacks linked to the nature of ashes and boost their benefits, but the energy needed to do this, can jeopardize their environmental interest and is commonly disregarded by researchers. This research investigates the benefits of processing SCBA by mechanical activation in the production of mortars and its environmental impact. It was found that treated ashes outperforms when substituting fine aggregates, increasing the compressive strength (CoS) of plain mortars by 62%. Despite the higher embodied carbon (EC) per cubic meter, treated SCBA in substitution of fine aggregates result in higher eco-strength efficiency, +32%. This enables the reduction of structural elements' sections diminishing the material use and the ultimate EC, named in this research as *specific embodied carbon*, up to 40%.

Key Words: Mineral admixtures, Embodied Carbon, Waste, Service Life

Introduction

Building materials and construction sector emissions entail up to 11% of annual global greenhouse gas (GHG) emissions. With a growing population and the demand of construction materials expected to double in the years to come, it is mandatory to act to reduce i) the exploitation of natural resources, ii) the CO_{2e} emissions, and iii) the waste landfilling, (Beiser, 2018; UNEP, 2016; WWF, 2018). Waste is also forecasted to escalate due to an increase in the living standards. In this scenario, waste is presented as a potential source of alternate materials to traditional natural resources. In the case of cementitious materials, the use of waste as cement or aggregate replacement, can enhance the mechanical and durability properties extending the service life of structures.

Some waste such as ashes resulting from industrial processes can show hydraulic or pozzolanic activity, promoting the generation of phases such as calcium silicate hydrates (CSH), (Cordeiro, Toledo Filho, Tavares, & Fairbairn, 2008; Pan, Tseng, Lee, & Lee, 2003). This refines the porous structure making the material less permeable to external harmful species, thus extending the service life of structures. In the case of artificial pozzolans, such as SCBA, the reactivity depends on the presence and quantity of amorphous particles, the oxides content (SiO_2, Al_2O_3 and Fe_2O_3, hereafter SAF) and the fineness (British Standard Institution, 2012b). However, industrial ashes may show important drawbacks that limit or hinder their use as pozzolans in concrete production as per to BS EN 450-1 requirements (British Standard Institution, 2012b). Some of these are i) high content in undesirable particles (organic matter, harmful substances, salts, porous and light particles), ii) an insufficient content of SAF (below 70%) or iii) a higher water demand due to the increased fineness or higher porosity. This makes researchers to treat ashes to boost the pozzolanicity to exceed the minimum strength activity index (SAI) required (75%) (British Standard Institution, 2012b).

Since emissions of cement are 185 times higher than those of aggregates (Jones, 2019), most of research is focused on using ashes in cement substitution (cs). The optimum substitution rate (sr*)* was established in 15-20% for ultra-treated ashes (Chusilp, Jaturapitakkul, & Kiattikomol, 2009; Rajasekar, Arunachalam, Kottaisamy, & Saraswathy, 2018). On the other hand, few researchers used SCBA in fine aggregate substitution (as) formulations, which optimum sr is not clear, (Modani & Vyawahare, 2013; Sales & Lima, 2010). However, the environmental impact of treatments, increasing the EC of the final product, is not commonly reported.

This research studies the environmental benefits of mortars containing treated SCBA (T-SCBA). To do this, comparisons were stablished with plain mortars and mortars containing untreated SCBA (Ut-SCBA). The influence of substitution of cement and fine aggregate was also investigated.

Materials and methods

Raw materials

Industrial SCBA from a 30MW energy plant in Dominican Republic was used. The combustion temperature was 750-800˚C. Ut-SCBA were ground, to mechanically activate the resulting ashes, labelled as T-SCBA. The grinding regime was the optimum one found previously as a part of the same research project. Ordinary Portland Cement (OPC), CEM I 52.5 and local commercial sand for construction purposes were used. The physical and chemical basic data of cement, sand and Ut-SCBA are shown in **Error! Reference source not found.**table 1.

Table 1

Physicochemical properties of raw materials

	CaO %	SiO_2 %	Al_2O_3 %	Fe_2O_3 %	SAF %	Cl^-_{ws} %	SAI %	D_{50} kg/m^3	ρ_r kg/m^3	ρ_b kg/m^3	SSA m^2/kg
OPC	76.5	18.7	3.3	3.1	25.0	-	-	39.6	3150	1400	163.5
Sand	0.3	7.6	3.2	0.3	-	-	-	476	2420	1635	36
Ut-SCBA	13.1	48.1	6.1	5.9	60.1	0.18	51	130.8	2449	718	442.8
T-SCBA	13.9	53.2	7.1	6.0	66.3	0.24	83	10.4	2551	928	817.1

ρ_b: bulk density; ρ_r: real density

Methodology

Preparation and curing of mortars

Mortars prisms (40x40x160mm) and cylinders (100x200mm) were casted as per BS EN 196-1 (British Standard Institution, 2016) by incorporating Ut-SCBA and T-SCBA in the substitution of cement/fine aggregate. The water to binder -the sum of cement and ash- ratio was adjusted to get the same flow value of control samples (w/b= 0.5). The sr were 0% (control) and 20% -as reported to be the optimal *one*-, (see table 2). Mortars were demolded after 24h and cured in tap water until testing date.

Table 2

Mix composition of mortars

ID	Description	CEM (kg)	Ash (kg)	Sand (kg)	w/b
Con	Control specimen	1	0	3	0.5
Ut-SCBA(cs)	Untreated ashes. Cement substitution	0.8	0.2	3	0.625
T-SCBA(cs)	Treated ashes. Cement substitution	0.8	0.2	3	0.525
Ut-SCBA(as)	Untreated ashes. Fine aggregates substitution	1	0.6	2.4	0.525
T-SCBA(as)	Treated ashes. Fine aggregates substitution	1	0.6	2.4	0.346

Testing of mortars performance

Fresh density of mortars was obtained as per BS EN 1015-6 (Bristish Standards Institution, 1999). The compressive strength (CoS) and total open porosity (OP) were obtained according to BS EN 196-1:2016 (British Standard Institution, 2016) and BS EN 1936:2006 (British Standard Institution, 2006), respectively, at 3, 7 and 28 days. Then, non-steady state migration values at 28 days, $D_{nssm-28}$ were obtained by means of rapid chloride migration test as per NT BUILD 492 (NORDEST, 1999) on control samples and Ut-SCBA and T-SCBA in *as* regime, since showed better mechanical performance.

Environmental assessment of mortars

Embodied carbon, EC. In this research the embodied carbon of mortars were calculated from the EC of raw materials as per equation (1).

$$CO_{2e} = \sum_{i=1}^{n}(CO_{2e-i} \; x \; W_i) \quad (1)$$

The EC of cement, fine aggregates and water were obtained from the references shown in table 3. The EC of Ut-SCBA and T-SCBA were estimated. Since SCBA is a waste from another industrial activity, in agreement to Sinoh et al. (2021), the resulted EC was that from transport and treatments. Transport was estimated under two scenarios: i) local use (in Dominican Republic) and ii) the exportation to United Kingdom (UK). In the first hypothesis, a round trip of 100 km (200 km) is covered by an average diesel heavy goods vehicle and average load. The second hypothesis contemplates a cargo ship and a distance of 6,836 km (one way). Additionally, the emissions due to treatments needed to obtain T-SCBA were calculated based on the laboratory machine characteristics. When scaling this up to industrial machines, more efficient results could be achieved.

Table 3

Embodied carbon of raw materials

Material				EC ($kgCO_{2e}/kg$)		Source
Average CEM I OPC				0.912		(Jones, 2019)
Fine aggregates				0.00493		(Jones, 2019)
Water				0.000149		(Government, 2022)
	Material processing	**Transport**		**Total**		
		Import	**Local**	**Import**	**Local**	
Ut-SCBA (as)	0	0.11	0.024	0.11	0.024	Estimated
T-SCBA (as)	0.35	0.11	0.024	0.46	0.374	Estimated

Eco-strength efficiency, ES_{CO2e}. This ratio assesses the emissions (CO_{2e}) against the strength capacity (CoS) as per equation (2). Including an additional functional unit facilitates the comparison between different materials performance. The carbon intensity is measured in $MPa/kgCO_{2e}$ so the higher the value, the more efficient the composition is.

$$ES_{CO2e} = \frac{CS}{CO_{2e}} \quad (2)$$

Specific embodied carbon, EC'. This concept, previously introduced by Torres de Sande et al. (2022b), meets the Structural Sustainable Design principles (Danatzko & Sezen, 2011) and evaluates the EC of a material considering the potential material reduction. This is obtained by defining a load acting on a specific geometry, in this case a cube (see figure 1). The minimum cube needed is then obtained considering a reduction factor of 1.5. Finally, the EC' of the cube can be obtained.

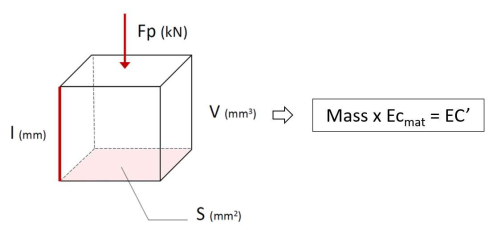

Figure 1. Specific embodied carbon approach

Service life assessment. The software Life-365 v.2.2.3.1 was used to obtained the corrosion initiation period of Control, Ut-SCBA(cs) and T-SCBA(as) samples. The diffusion of mortars at 28 days were obtained from RCMT. The concentration of chlorides at the surface of the reinforcing steel rebars to initiate the corrosion (%wt. of mortar) was calculated in 0.1% based on the commonly threshold used of 0.4% (wt. of cement). Marine tidal zone was selected as exposure condition and a cover of 50mm was defined. The supplementary cementitious materials (SCM) influence the rate of reduction in diffusivity, thus the *m*-value -that indicates the opposition of the composition to the chlorides penetration-. Since unknown, *m*-value was hypothesized by depicting two scenarios:

A. All samples have the same *m*-value (*m=0.20)*, the one calculated by the software for control samples. The software is originally designed for concretes, thus variations may occur.

B. A *m*-value of 0.60 -which is the value for fly ash (50% of wt of cement) and better represents the case of T-SCBA- to consider the influence of using SCM in the reduction in diffusivity.

Results and Discussion

Influence of Mechanical Activation in Properties of Mortars

Table 4 show the results for open porosity, compressive strength and D_{nssm} for the corresponding testing dates. The results are discussed below.

Table 4

Open porosity, compressive strength and Dnssm of mixes

	Open porosity, %			Compressive strength, MP			$D_{nssm-28d}$, $x10^{-12}m^2/s$
	3d	7d	28d	3d	7d	28d	28d
Control	21.7	19.2	17.2	23.2	29.3	36.1	26.77
Ut-SCBA(cs)	26.9	24.8	26.1	11	12.9	17	-
T-SCBA(cs)	22.9	22.5	20.8	7.4	14.9	22.4	-
Ut-SCBS(as)	28.8	26.1	25.5	13	13.3	23.7	14.23
T-SCBA(as)	17.3	13.9	11.1	33.2	40.5	58.5	2.59

Open porosity

Ut-SCBA increases the OP of mortars at 28 days by 52%(cs) and 48.2%(as*)* due to a higher water demand and the incorporation of more porous structures. T-SCBA reduces the OP of Ut-SCBA by breaking down these structures. However, only in *as* systems, T-SCBA reduces the porosity of control samples -since early ages - by 35.5% due to a major reactivity and packing effect of ashes.

Compressive strength

CoS of T-SCBA at 28 days outperformed that of Ut-SCBA by 31.7%(cs) and 147%(as) and that of control samples by 62% when substituting aggregates; however, reduced the CoS between 38% (cs) in comparison to control samples, (see table 4). T-SCBA(as) boosts the strength gain since early ages, usually delayed in mixes containing pozzolans. These improvements are attributable to a highest SSA of T-SCBA, that promotes the pozzolanic reaction, the provision of more nucleation sites, and the packing effect of unreactive fines (Torres de Sande et al. 2022a). The densification of the matrix is supported by the reduced OP of mortars containing T-SCBA, 11.1%, in comparison to the 17.2% of control samples.

Non-steady state migration, D_{nssm}.

The addition of Ut-SCBA and T-SCBA reduces the D_{nnssm} of control samples by 46.5% and by 90%, respectively. Hence, regardless the mechanical performance, the addition of SCBA can increase the chloride penetration resistance of mortars and, by extension, of concrete.

Embodied Carbon of Mortars.

When used locally both, Ut-SCBA and T-SCBA, reduce the EC/m^3 of mortars when substituting cement by 19.2% and 11.6%, respectively, (figure 2). Due to the lower EC of natural aggregates in comparison to that of cement, Ut-SCBA and T-SCBA increase the EC of mortars by 1.2% and 23.9% when substituting fine aggregates. Freighting ashes from Dominican Republic to UK increases the EC of carbon up to 2.3% and 5.5% for cement and fine aggregates substitution, respectively. The difference lies in the higher amount of ashes per volumetric unit of the latter.

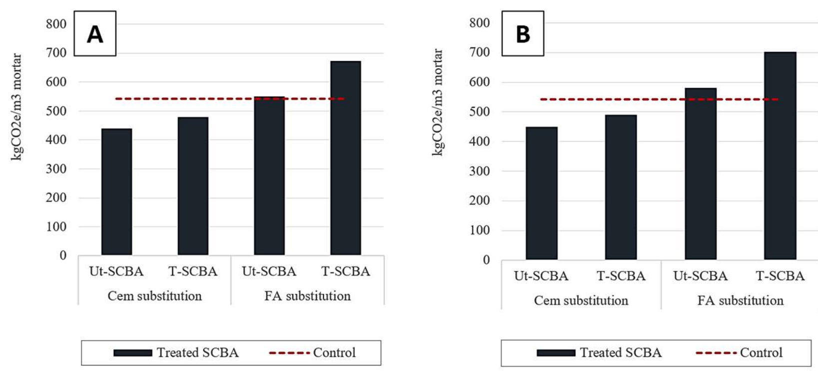

Figure 2. EC of mortar compositions when (a) using SCBA locally or (b) importing in UK.

Eco-strength Efficiency, ES_{CO2e}.

Figure 3a and figure 3b show the Eco-strength efficiencies at different ages for cement and aggregates substitution, respectively. T-SCBA(as) is the only scenario in which the efficiency outperforms that of control samples, obtaining a strength gain of 32% per kg of CO_{2e} emitted, at 28 days. In this scenario, the treatment that initially deliver mortars with higher EC, results in an increase in efficiency of 50.6% in comparison to Ut-SCBA. While the difference between using Ut-SCBA as aggregate substitute against cement substitute is 9.3%, this value turns 85% when using T-SCBA.

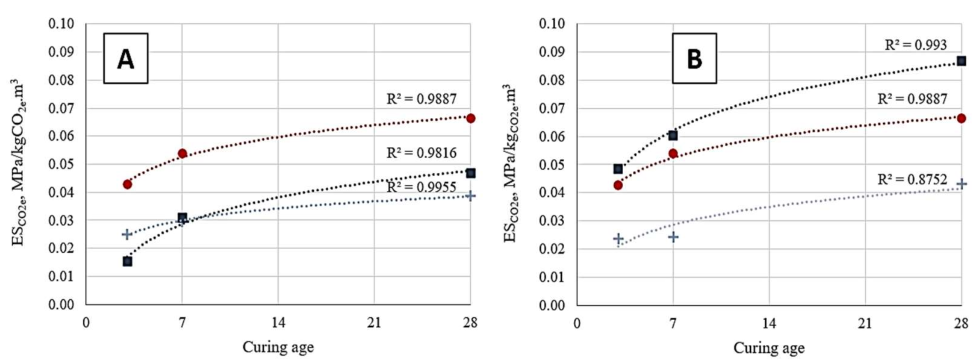

Figure 3. Eco-strength efficiency of mortars using Ut-SCBA and T-SCBA in cement substitution (a) and fine aggregates substitution (b). Local use.

Specific Embodied Carbon, EC_e.

Figure 4 shows the equivalent cubes, when using different compositions, able to bear a 100kN load and figure 5 shows the corresponding specific carbon. The volume of material needed for a cube able to bear the mentioned load when adding T-SCBA(as) is halved with respect to control mortars and one forth with respect to T-SCBA(cs).

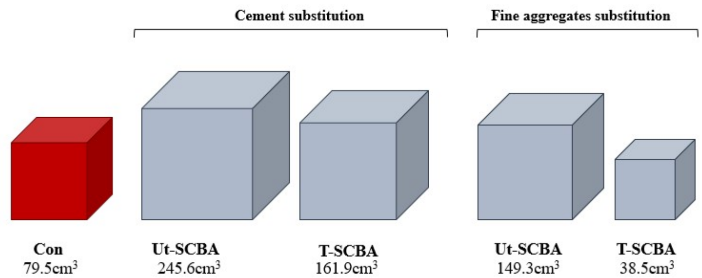

Figure 4. Specific embodied energy, $kgCO_{2e}$

When multiplying the resulting volume by the EC ($kgCO_{2e}/m^3$) of each mortar, the specific embodied carbon, EC', for each cube is obtained, (see figure 6). The EC' of T-SCBA(as) mortars is 40% lower than that of control samples, a third part of that T-SCBA(cs) mortars and a forth part of Ut-SCBA(cs) mortars. This type of approach offers a more realistic comparison among different compositions.

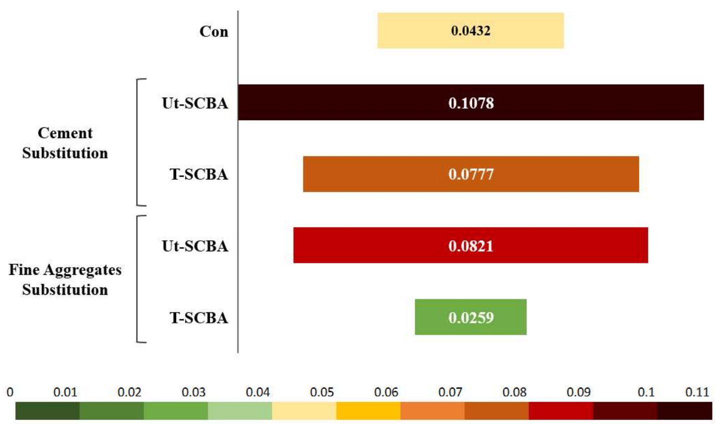

Figure 5. Specific embodied energy, $kgCO_{2e}$

Service life improvement

Figure 6(a) shows the initiation period scenarios in which the *m*-value is considered to be that provided by the software for cement composition, m=0.2. Being extremely conservatives by equaling *m*-value, the T-SCBA(as) extends the initiation period by 9 and 7 times and nine times in comparison to control samples and Ut-SCBA, respectively. When assimilating the *m*-value of T-SCBA(as) to that of mixtures containing FA, the results show an outstanding performance, being the only adequate composition for marine tidal exposure, (see figure 6(b)).

When the cover thickness is reduced by 25%, under the same parameters used above to obtained figure 6(b), the initiation period obtained was 89.3years, indicating that the potential reduction of material consumption defended when assessing the specific embodied carbon still provides higher durability properties. To obtain more accurate results and a complete life cycle assessment, electrochemical methods are needed to get a thorough understanding of the durability properties of these materials.

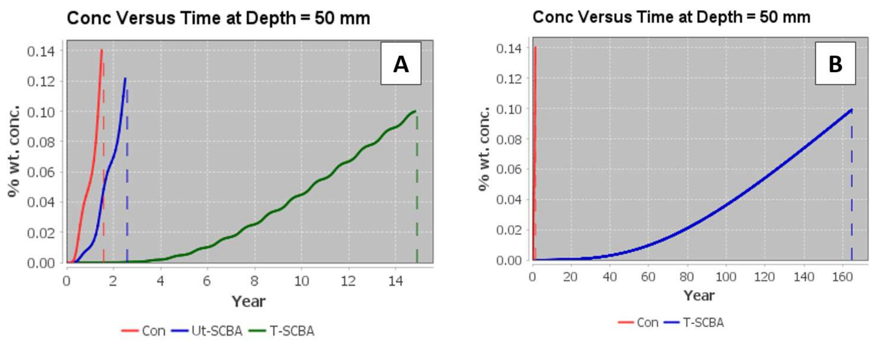

Figure 6. Initiation period when considering a) *m* = 0.2 and b) *m* = 0.6

Conclusions

The benefits of treating SCBA were investigated in different mix compositions. Additionally, the environmental impact was assessed, demonstrating the importance of the proposed approach when potential low-carbon materials are investigated. It was concluded that:

- SCBA not considered as artificial pozzolans according to the limit SAF>70%, can provide low-carbon materials when using a proper approach.
- Mechanical activation of Ut-SCBA (T-SCBA) highly improved the mechanical performance of mortars in aggregates substitution system (increase of 62% in CoS and reduction in OP by 35.5% at 28 days)
- The initial higher EC of T-SCBA(as) can be reduced if other variables are included in the evaluation as functional units, such as the CoS or the material reduction. T-SCBA(as) composition is the only one showing a higher Eco-strength efficiency than control samples. Its specific embodied carbon was reduced by 40% and the material consumption was halved.
- Based on the D_{nssm}, the initiation period of T-SCBA(as) mortars is highly extended.

Beiser, V. (2018). *The world in a grain: the story of sand and how it is transformed civilization* (First Edition ed.): Riverhead Books.
British Standard Institution (1999) EN 1015-6:1999. Methods of test for mortar for masonry. Part 6: Determination of bulk density of fresh mortar
British Standard Institution. (2006). BS EN 1936: 2006. Natural stone test methods. Determination of real density and apparent density, and of total and open porosity.
British Standard Institution. (2012b). BS EN 450-1:2012. Fly ash for concrete. Definition, specifications and conformity criteria.
Institution, B. S. (2016). BS EN 196-1:2016. Method of testing cement. Part 1: Determination of strength.

Chusilp, N., Jaturapitakkul, C., & Kiattikomol, K. (2009). Utilization of bagasse ash as a pozzolanic material in concrete. *Construction and Building Materials, 23*(11), 3352-3358. doi:https://doi.org/10.1016/j.conbuildmat.2009.06.030
Cordeiro, G. C., Toledo Filho, R. D., Tavares, L. M., & Fairbairn, E. M. R. (2008). Pozzolanic activity and filler effect of sugar cane bagasse ash in Portland cement and lime mortars. *Cement and Concrete Composites, 30*(5), 410-418. doi:https://doi.org/10.1016/j.cemconcomp.2008.01.001
Danatzko, J. M., & Sezen, H. (2011). Sustainable Structural Design Methodologies. *Practice Periodical on Structural Design and Construction, 16*(4), 186-190. doi:doi:10.1061/(ASCE)SC.1943-5576.0000095
Government, D. f. B. E. I. S. H. (2022). *Greenhouse gas reporting: conversion factors*.
Jones, C. (2019). *The Inventory of Carbon and Energy - ICE Database*.
Modani, P. O., & Vyawahare, M. R. (2013). Utilization of Bagasse Ash as a Partial Replacement of Fine Aggregate in Concrete. *Procedia Engineering, 51*, 25-29. doi:https://doi.org/10.1016/j.proeng.2013.01.007
NORDEST. (1999). NT BUILD 492. Concrete, mortar and cement-based repair materials: Chloride migration coefficient from non-steady-state migration experiments
Pan, S.-C., Tseng, D.-H., Lee, C.-C., & Lee, C. (2003). Influence of the fineness of sewage sludge ash on the mortar properties. *Cement and Concrete Research, 33*(11), 1749-1754. doi:https://doi.org/10.1016/S0008-8846(03)00165-0
Rajasekar, A., Arunachalam, K., Kottaisamy, M., & Saraswathy, V. (2018). Durability characteristics of Ultra High Strength Concrete with treated sugarcane bagasse ash. *Construction and Building Materials, 171*, 350-356. doi:https://doi.org/10.1016/j.conbuildmat.2018.03.140
Sales, A., & Lima, S. A. (2010). Use of Brazilian sugarcane bagasse ash in concrete as sand replacement. *Waste Management, 30*(6), 1114-1122. doi:https://doi.org/10.1016/j.wasman.2010.01.026
Sinoh, S. S., Ibrahim, Z., Othman, F., Kuang, L. M., & Zaki, A. (2021). *Life Cycle Assessment of Sugarcane Bagasse Ash as Partial Cement Replacement in Concrete.* Paper presented at the Proceedings of the 4th International Conference on Sustainable Innovation 2020–Technology, Engineering and Agriculture (2020).
Torres de Sande, V., Sadique, M., Bras, A., & Pineda, P. (2022a). Activated sugarcane bagasse ash as efficient admixture in cement-based mortars: Mechanical and durability improvements. *Journal of Building Engineering*, 105082. doi:https://doi.org/10.1016/j.jobe.2022.105082
Torres de Sande, V., Sadique, M., Bras, A., Medina-Carrasco, S., Fubara, T., & Pineda, P. (2022b). *Eco-Strength Efficiency and Specific Embodied Carbon of Low-Co2eq Cementitious Materials Using Industrial Sugarcane Bagasse Ash (preproof version)*
UNEP, U. N. E. P. (2016). Global Material Flows and Resource Productivity. Assessment report for the UNEP international resource panel.
WWF. (2018). Impacts of Sand Mining on Ecosystem Structure, Process and Biodiversity in Rivers. . In L. Koehnken & M. Rintoul (Eds.).

ASC Conference Proceedings: Thematic Review of Considerations, Contributions and Capturing Trends in Academia and Industry

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For over half a century, the Associated Schools of Construction (ASC) conference has progressively contributed to the built environment both in academia and industry. ASC Conference uses education and practice as the main themes to channel papers that range across different built environment disciplines. Although most contributions to the ASC conference were facilitated by US-based institutions, there is a growing international interest, hence, it is vital to recognize conference considerations, contributions to academia and the industry and shed the light on future trends. This paper attempted to thematically review ASC proceedings from 2002-2021 retrieved from ASC archives with a total of 1317 manuscripts. The findings revealed that the main themes of academia and industry have been equally recognized in the ASC conference proceedings with a noticeable rise toward industry-based publications in recent years. As resulted from thematic analysis, 11 main publication disciplines were proposed. The construction management, risk management and sustainability disciplines have been mostly served among the proposed disciplines. The trend analysis highlighted the growing tendency to integrate technology features into academia and industry research. Finally, the key research findings facilitate a robust mechanism to determine future ASC conference themes while unveiling avenues to expand international outreach and exposure.

Key Words: Education, Industry, Discipline, Technology

Introduction

Construction is recognized as one of the most data/information intense industries as it includes multiple lifecycle phases with interdisciplinary integration of systems and stakeholders (Luo et al., 2022). It is noted that construction, is the leading contributor to GDP in many countries, in terms of infrastructure development, housing development and employment opportunity generation (Nguyen and Le, 2022). Therefore, knowledge sharing, and exchange has become an evitable component that enables long-term value and impact creation within such an industry. Besides national/international exhibitions, seminars and workshops, the conferences facilitate interactive environments that motivate the learning and development process, especially in rapidly paced industries such as construction. At an international level, the International Council for Research and Innovation in Building and Construction (CIB) formed one of the earliest construction conferences in 1950, which was held in Geneva and called the Conference of Building Research (CIB, 2022), which follows by the first CIB world congress in 1965, and to this day, CIB can be seen as one of the major channels that interconnect construction research and practice worldwide. For over half a century, and simultaneously with the start of CIB's first world congress, the Associated Schools of Construction (ASC) has been one of the major hubs that connected construction professionals from the education and industry sectors (ASC, 2021) in the United States.

The ASC annual conference has the vision of inspiring excellence in construction education and research while providing robust channels for advancing and sharing good practices, driving innovation and building an international community. In recent years, with the rising attention in the construction industry, many other conferences with international outreach were established such as the Association of Researchers in Construction Management (ARCOM), International Conference on Construction Applications of Virtual Reality (CONVR), and many others including CITC, EPPM and E3C. Although the ASC Conference, compared to many other construction conferences, has a longer and well-established history, the contributions were mostly channeled by US-based institutions. More importantly, whilst the ASC lists several key themes for each conference, the proceedings are categorized into education and industry-based publications. Although this offers a tailored approach to map publications to both industry and academia, it does not provide insight into the conference's exposure and contributions across different disciplines over the years. Therefore, this research aims to thematically review ASC proceedings to identify the conference considerations, contributions and future trends with a direct emphasis to provide more tailored impact and exposure internationally.

Research Methodology

As discussed above, the main focus of this study is to conduct a thematic review of ASC conference proceedings from 2002-2021 to better acknowledge the conference trends in order to explore avenues that support boosting ASC conference outreach and impact internationally. Accordingly, three research questions were set in this study as follows.
Q1: Who were the key contributors to the ASC conference over the past two decades and which built environment disciplines have been considered over the years?
Q2: What were the contributions of ASC conference publications towards academia and the industry and what were the research technological trends that emerged over the past years?
Q3: What are the potential strategies to boost ASC conference outreach and impact internationally?

The objective of Q1 was first to identify the jurisdictions and the academic universities that contributed to the conference over the years and then to explore their commitments towards the key built environment disciplines such as construction management, project management, risk management, and sustainability to name a few. The Q2 mainly focused on identifying the contributions from the ASC conference publications to academia and the construction industry. Besides, the research trends over the years needed to be explored while determining the emerging research trends for the two decades. Thereafter, Q3 was formed to explore the strategies to uptake ASC conference outreach and impact with the identified emerging trends, opportunities and possibilities. Figure 1 presents the overall research approach followed in this study. According to Figure 1, all the ASC conference papers from 2002 to 2021 were downloaded from the ASC website and developed a database (including publication year, article title, origin, contributing university/organization based on the first author, discipline considered by the paper, contribution to the academia or the industry, and emerging trends) in order to proceed with the analysis. The collected database was visualized using Power BI and then analyzed using thematic analysis to find out answers for Q1-Q3. Thematic analysis was beneficial in identifying the common themes underlying the papers (Vaismoradi et al. 2013) that help to understand their contribution towards research disciplines and phases while determining the new imperatives for research trends. In order to provide a focused approach towards mapping ASC proceedings to different disciplines, the authors have classified the papers against 11 disciplines (see Table 1), and this allowed a more structured and logical way of analyzing the contributions.

Table 1

Disciplines used to classify contributions from ASC Proceedings

Discipline	Areas
Construction Management	Site Management, Planning and Scheduling, Resource Management, Manufacturing and Production, Equipment Management.
Project Management	Integration and Scope Management, Quality Management, Procurement Management, Stakeholder Management.
Risk Management	Health and Safety, Procurement Risks, Safety Management.
Interdisciplinary	Academic: pedagogy, learning and review-based research. Industry: Engaging multiple disciplines.
Sustainability	Social, Environmental, Economic, Energy Efficiency.
Civil Engineering	Structural Engineering, Transportation Engineering, Water Engineering, Soil Mechanics.
Facilities Management	Operational Management, Maintenance Management.
MEP	Mechanical, Electrical, Plumbing
Cost Management	Quantity Surveying, Quantity Takeoffs, Cashflow.
Skills and Development	Soft Skills, Technical skills
Employability	Training, Internships, Careers

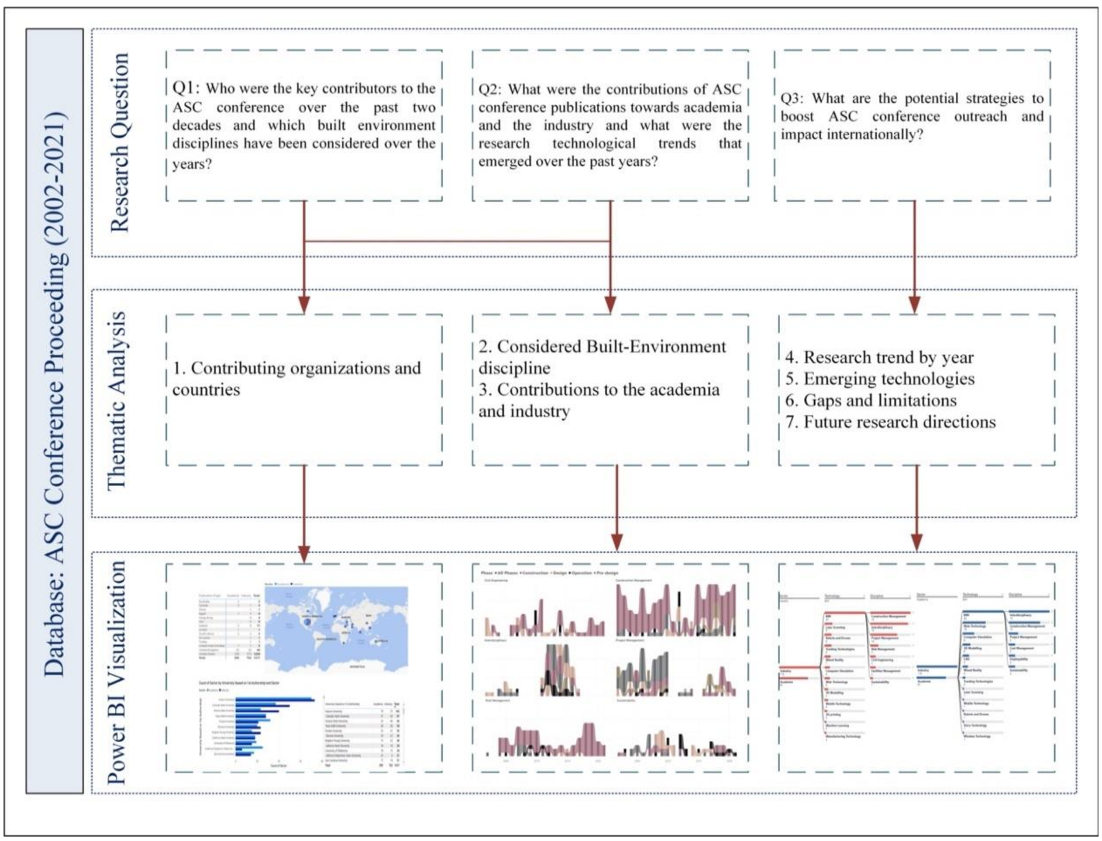


Figure 1: Research approach deployed in this study

Results and Discussion

This section views and discusses the results derived from the thematic analysis and Power BI visualization. In total, 1317 manuscripts were analyzed from 2002-2021 where all data was imported to Microsoft Power BI for data visualization. In order to provide a structured and logical analysis, the results are classified into three parts: ASC outreach and exposure, contribution towards different disciplines with phases, and finally ASC's future trends and potentials.

ASC Outreach and Exposure

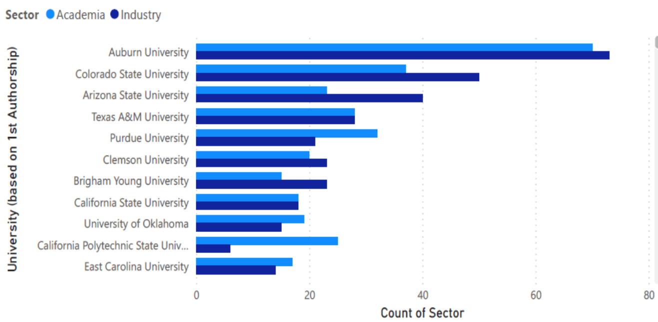
Referring to the refined database collected prior, information related to the country of publication and origin university along with types of contribution academia/industry categories were identified and illustrated (See. Figure 2). According to Figure 2, in two decades, participants in the conference originated from fourteen different countries while the majority were from the USA (i.e. More than 80%) and in second order from the UK. A very limited number of manuscripts were submitted from the Middle East, Africa, and Australia. By marking participants' countries in the world map, it is observed that zero engagement has been recorded for South America and North Asia while in Europe with exception of the UK and Ireland no other country participated in an ASC conference since 2002. A low level of engagement from other counties could be because almost the majority of the ASC conference occurrences have been held in the USA, while in many respects travelling for attending in the USA can be hard for willing participants from another side of the world. This claim can be proved by referring to 2012 as the conference was hosted by Birmingham City University in the UK where the level of international engagement increased clearly.

Publication Origin	Academia	Industry	Total
Australia	2		**2**
Canada	3	1	**4**
China		1	**1**
Egypt	1	5	**6**
Hong Kong		4	**4**
Iran		6	**6**
Ireland	5	6	**11**
Jordan	1		**1**
South Africa	2	2	**4**
Sri Lanka		1	**1**
Turkey		1	**1**
United Arab Emirates	1	1	**2**
United Kingdom	22	22	**44**
United States	558	672	**1230**
Total	**595**	**722**	**1317**

Figure 2: ASC Conference outreach and exposure worldwide in terms of both Academia and Industry.

As the majority of published papers in ASC conferences originated from the USA (i.e. a total of 1220 out of 1317), it was interesting to know how participating universities located in the USA tend submitting papers covering academia or the industry sector. A bar chart was created to assess the count of the sector against the USA-based university (based on 1st Authorship). Among eleven USA-based universities engaged in the ASC conferences series, Auburn University has been recorded with the highest number of papers with an almost equal level of engagement in both academia and industry (Figure 3). The same attitude was observed at Texas A&M University, Clemson University, California State University and East Carolina University. Universities like Colorado State University, Arizona

State University and Brigham Young University reported a higher contribution toward industry in comparison to academia, while on other hand California Polytechnic State University, Purdue university and the university of Oklahoma has submitted manuscripts majority covering areas related to academia.



University (based on 1st Authorship)	Academia	Industry	Total
Auburn University	70	73	**143**
Colorado State University	37	50	**87**
Arizona State University	23	40	**63**
Texas A&M University	28	28	**56**
Purdue University	32	21	**53**
Clemson University	20	23	**43**
Brigham Young University	15	23	**38**
California State University	18	18	**36**
University of Oklahoma	19	15	**34**
California Polytechnic State University	25	6	**31**
East Carolina University	17	14	**31**
Total	**595**	**722**	**1317**

Figure 3: Organizational contribution towards ASC Conference

ASC Contribution to different Disciplines and Phases (2002-2021)

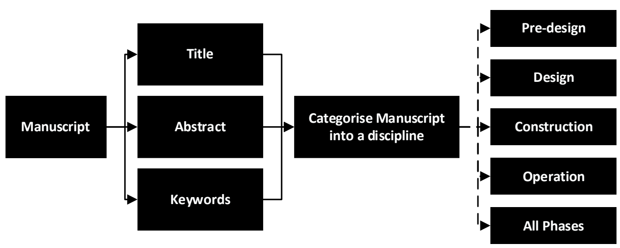


Figure 4: Process followed when classifying manuscripts to disciplines and phases.

From the database generated, and as shown in Figure 4, the authors have mapped the manuscripts to 11 disciplines (explained in the methodology) and contextualized the discipline (where possible) to one or multiple phases in the lifecycle of a construction project. To provide more focused insight, the authors have only shown the disciplines that received most contributions (see figure 5). It was found that from 2002-2021, the disciplines that received the most attention, in both academia and industry, within the ASC conference are Construction Management, Risk Management and Sustainability. In terms of Construction Management, it is noticed that most efforts were within the construction phase including planning and scheduling (e.g. Woods, 2006), manufacturing methods (e.g. Olsen and Ralston, 2013), resource management, site management and equipment management. In the context of the United States, this can be reasoned by the fact that Construction Management is one of the most common programs across U.S. institutions, and the vast collaborations between academia and industry which provides solid and sustained knowledge transfer that resulted in many industry-based contributions. It is also noted that most international contributions were within the Construction Management discipline and were more industry-based. Similar to contributions within the Construction Management discipline, contributions within Risk Management are considerably and mostly focused on areas within the construction phase. The analysis noted that a high number of contributions were within health and safety and safety management. In the case of both Construction Management and Risk Management, the high number of contributions was mostly contextualized within the construction phase, which is recognized as an attractive thread of continual and progressive research in the United States. According to a study by Lee et al. (2013), it was noted that research within construction management in universities attracts an average of USD 250K, and in some universities can reach up to USD 1$. Another study indicated that internationalized disciplines such as Construction Management have a certain amount of ‘interpretive flexibility’, which allows them to be shaped or mutated in different ways allowing both academics and practitioners more opportunities to continue research (Harty and Leiringer, 2017) On the contrary, contributions within the Sustainability discipline, although less when compared to Construction Management and Risk Management, was recognized to be more overarching and touched across different phases across the whole lifecycle. Whilst this reflects a great and well-sustained impact of contributions on sustainability across different phases, future considerations should be tailored to map contributions against Sustainability Development Goals (SDGs) to illustrate more impactful research for both academia and practice. From another perception, contributions within Project Management and Interdisciplinary disciplines had a noticeable impact period. It is imperative to recognize that contributions in both Project Management and Interdisciplinary research, despite discontinuity when compared with other disciplines, are the most interconnected with different phases in a lifecycle of a project. Whilst project management contributions have recognizably fallen following 2010, a major peak in contributions has risen in Interdisciplinary Research from 2010 onwards. The exponential rise in Interdisciplinary research can be reasoned by many factors including the technological wave and industry 4.0 (Schonbeck et al., 2021), and the adaptation of different approaches, tools and processes from other industries (Connaughton and Collinge, 2021). In fact, interdisciplinary research allowed more channels for impactful research contributions within the ASC conference by integrating multiple disciplines to generate value and interconnect a wider range of stakeholders.

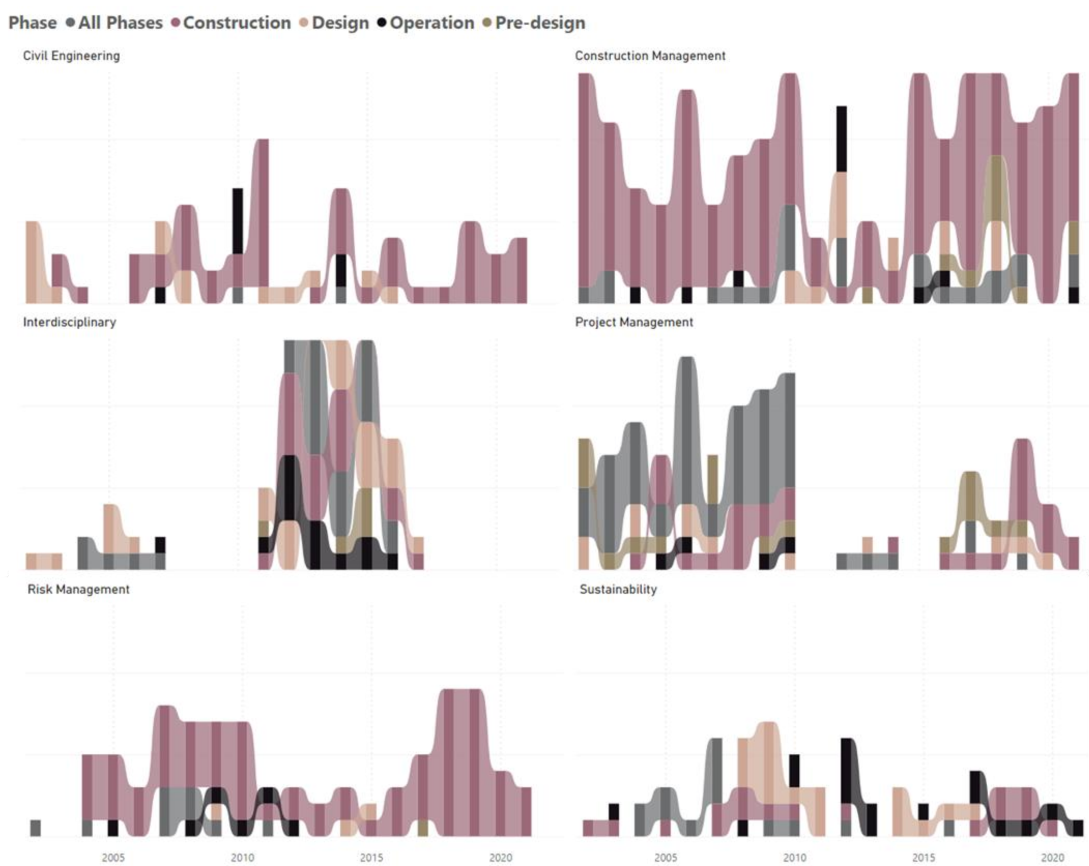


Figure 5: Disciplines that received most contributions in the ASC Conference

Emerging technologies in ASC conference proceedings

Figure 6 presents the 'technological' trend of the publications towards industry and academia. It is not surprising to see that Building Information Modelling (BIM) has received the highest attention from both academia and the industry and facilitating leading-edge technological innovation and contribution. The first paper related to BIM was published in 2006 (Gier et al., 2006) and it mainly contributed to academia in terms of teaching productivity analysis. In the following years, published research on BIM became more industry-focused. Not only limited to identifying advantages and challenges in BIM implementation in different construction disciplines such as construction management (Goucher and Thurairajah, 2012) and facilities management, the conference focus has been extended towards integrated project delivery (Mayouf et al., 2019), site planning and management, risk management, sustainability and interoperability of BIM. Besides, the latest trend is on the integration and interoperability of BIM as shown in the recent ASC publication of 'BIM-GIS: Analysis and Integration for Contractors'. It is important to note that some publications have tailored BIM towards sustainability across different phases, and this supports different interventions related to sustainability challenges, especially for the industry. BIM studies in academia were more interdisciplinary research that captured developing pedagogies, capstone projects and undergraduate education. This is recognized particularly in published research from 2013/2014 where ASC experienced a peak in interdisciplinary research. Besides major contributions towards BIM, another significant interest of the conference contributors was in laser scanning and robots and drones. Laser scanning and drones are important technologies in earthmoving operations and surveying work and the publications were appropriately in the same disciplines. Indeed, the utilization of robots in construction progress monitoring was an interesting paper which drags the attention of the readers to recent industry innovations. Concerning tracking technologies, barcodes and RFID technologies were assessed in recent years. The mixed reality was inclusive of augmented and virtual reality and their combinations. 3D printing, another emerging technology was studied for its feasibility in Spall Damage Rehabilitation. Emerging trends in manufacturing technologies were also found since 2011 and are mostly towards modular construction development which is highly demanded by the industry.

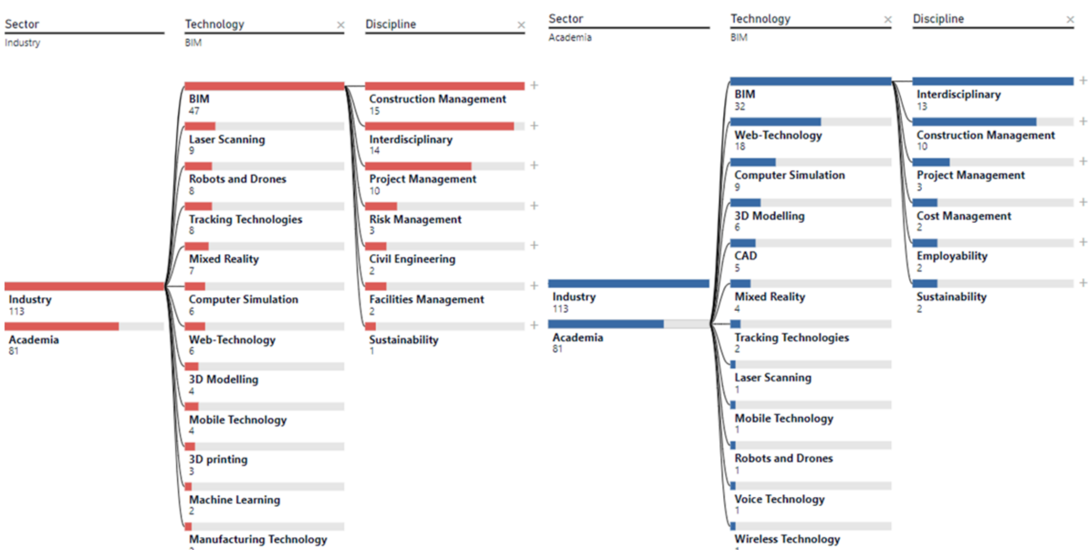


Figure 6: Capturing 'technological' trends of ASC conference publications

In academia, web technology has received the second topmost interest as a result of the significant implementation of web conferencing and other web-based systems for learning, education, planning industry operations, and simulation purposes. Deployment of web technology was urged and demanded by both academic and industrial organizations to cope with the Covid-19 emergence and disruptions caused by the pandemic. Computer simulations including computer games are other thought-provoking areas that are covered in the conference with great significance in construction education. All these simulation studies recreate similar virtual environments and are highly supportive of learning, education, and training. Undoubtedly, the future interest of the conference would be even more on BIM, mixed reality, web technologies, computer simulation, 3D printing and modelling, manufacturing technologies and robotics. However, it is much more exciting to see the conference publications are directed and focused beyond productivity and efficiency as the sole goals and boost the role and the contribution of industry to society which is emphasized in industry 5.0. Therefore, human-centric design tools and sustainable and resilient technologies would emerge as appealing technologies without reinventing the wheel. Finally, the country-specific priorities (such as net-zero Carbon strategy implementation in the UK) could be identified by extending the geographic horizons of the conference.

Conclusions and future research directions

To sum up, this research aimed to thematically review ASC proceedings to highlight consideration, contributions and capturing trends. A total of 1317 manuscripts were analyzed from the period 2002 (the first ASC online published proceedings) to 2021. As the conference originated in the U.S., it was expected that contributions were 80% from the U.S. based institutions and organizations where Auburn University was identified as the most contributing university. Internationally, most contributions were industry-based papers, and the United Kingdom (UK) was identified with the highest number of contributions in both education and industry papers. To identify and tailor contributions from both Academia and Industry papers, 11 disciplines were identified where each paper was classified according to the relevant discipline, and where applicable, each paper was contextualized to a phase within the lifecycle of a construction project. It was found that among the proposed disciplines, construction management, risk management and sustainability disciplines had the most contributions. It was also found that there is a major growing interest in interdisciplinary research, and this portrayed great potential to encourage the integration of such themes in future ASC conferences. Finally, when looking into emerging technologies within the ASC conference, it was found that BIM had the top attention in both academia and industry since 2010. In Industry-based papers, it is recognized that there is a growing interest in autonomous technologies such as robots and drones, mixed reality and also laser scanning whilst academia-based papers revealed an ongoing progression to demonstrate the impact of web-based technologies, computer simulations and also mixed reality. One of the major implications of looking into emerging technologies within the ASC conference is recognizing their impact across different disciplines, and more importantly, using the findings as a benchmark to integrate technologies with a higher impact in future ASC conferences. It is essential that, for future ASC conference, to encourage contributions into disciplines that are positioned within the operational phase such as facilities management, building performance and smart systems. Although this research elicited many interesting findings especially in highlighting the different impacts of the ASC conference, it is important to highlight potential limitations, which can be addressed in future conferences. The first limitation is the abstraction of disciplines, which mainly relied on the title of the papers, keywords and abstract, hence future research may look into further and perhaps more overarching classification. Another limitation is the contextualization of different manuscripts across phases, which primarily relied on the interpretation of the authors. Future work looks into deeper and more insightful disciplines with the most contributions to providing more informative directions for the upcoming ASC conferences.

References

Associated Schools of Construction (ASC)., 2022. ASC History. Available at: https://www.ascweb.org/ (Accessed on 2nd October 2022).

CIB – International Council for Research and Innovation in Building and Construction., 2022. The History of CIB. Available at: https://cibworld.org/the-history-of-cib/ (Accessed on 20th October 2022).

Connaughton, J. N. and Collinge, W. H., 2021. Trialling a new approach to interdisciplinary collaboration in UK construction: A projects-as-practice analysis. Construction Management and Economics, 39(7), pp. 881-893.

Gier, D.M., Loftin, E. and Coogan, K., 2006, April. Are Building Information Models effective for teaching productivity analysis. In *ASC Proceedings of the 42nd Annual Conference* (pp. 20-22).

Goucher, D. and Thurairajah, N., 2012. Advantages and challenges of using BIM: A cost consultant's perspective. In *49th ASC Annual International Conference, California Polytechnic State University (Cal Poly), San Luis Obispo, California*.

Luo H., Lin, L., Chen, K., Antwi-Afari, M. F. and Chen, L. 2022. Digital technology for quality management in construction: A review and future research directions. Developments in the Built Environment, 12, 100087.

Harty, C. and Leiringer, R., 2017. The future of Construction Management Research. *Construction Management and Economics*, 35(1), pp. 1-12.

Lee, S., Esmaeilzadeh, A. and Lee D-E., 2013. Graduate construction management programs in the U.S.: Lessons from leading institutions. *KSCE Journal of Civil Engineering*, 17(7), pp. 1664-1671.

Mayouf, M., Kilby, A. and Kennedy, R., 2019. Informing Future Learning Pedagogy towards Integrated Project Delivery (IPD) in the UK. *55th ASC Annual International Conference*, University of Denver, Denver, Colorado.

Nguyen, D. T. and Le, P. L., 2022. Twenty-year application of logistics and supply chain management in the construction industry. *Construction Management and Economics*, 40(10), pp. 796-834.

Olsen, D. and Ralston, W., 2013. Utilizing Prefabrication in Lean Construction: A Reasoned Decision or an Educated Guess?. ? *49th ASC Annual International Conference Proceedings*.

Schonbeck, P., Lofsjogard, M. and Ansell, A., 2021. Collaboration and knowledge exchange possibilities between industry and construction 4.0 research. *25th International Conference on Knowledge-Based and Intelligent Information & Engineering Systems*, 192, pp. 129-137.

Vaismoradi M, Turunen H, Bondas T. 2013. Content analysis and thematic analysis: Implications for conducting a qualitative descriptive study. *Nurs Health Sci*. 15(3):398–405.

Woods, P., 2006. Tool Management in Construction: An Initial comparison of accuracy and scan times for RFID and Bar Code Systems. *ASC Proceedings of the 42nd Annual Conference Colorado State University Fort Collins, Colorado April 20 – 22.*

Synergizing Case-Based Learning and Industry Involvement in a CEM Course – A Case Study

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This paper synthesizes the lessons learned from the experience of developing and teaching a Case-Based Learning (CBL) course in Construction Engineering and Management (CEM) with a diverse group of industry partners. The authors analyzed and compared the participants' reflections on their experiences throughout the course to identify: 1) the factors that may foster and hinder students' learning and 2) potential opportunities and challenges of interacting with industry practitioners when using CBL as the core teaching strategy in a CEM course. While structuring the course, instructors should invest time in increasing the navigability of practitioners' supplemental material and guiding students through it. Case order matters –complexity and uncertainty should increase as students gain confidence with CBL—and including deliberate team preparation time was highly welcomed by students. Practitioners' presence in the classroom increased case credibility, which resulted in more self-reported student engagement. Welcoming more actors allows students to analyze the cases from diverse points of view. Instructors should act as discussion facilitators. Looking forward, practitioners should start documenting the alternatives considered beyond the definitive solution of a case to enrich the case's contents. These outcomes provide instructors interested in implementing CBL in their engineering courses with insights grounded in experience that will ease the process from ideation to delivery.

Key Words: Case-Based Course, Industry Practitioners, CEM Education, Academy-Industry Partnership

Introduction

Higher-education programs in Construction Engineering and Management (CEM) face the challenge of helping students prepare for careers in a demanding industry that requires that they make accurate decisions and offer innovative solutions to problems embedded in real-world scenarios from day one. However, typical teaching strategies in CEM often fail to portray the actual conditions in which such problems occur, and such decisions must be made. Therefore, new CEM professionals regularly find it difficult to navigate the interdisciplinarity, complexity, and uncertainty that characterizes CEM practice. Consequently, they constantly express that much of the knowledge they gained during their studies lacks direct applicability.

Case-based learning (CBL) emerged as an alternative to address this educational challenge. CBL aims to provide students with faithful representations of the contexts and situations in which professional practice occurs (the cases). It emphasizes critical analysis and judgment of contextual information and its integration with theory for problem-solving and decision-making (Safapour et al., 2019). In other words, CBL allows students to apply their prior knowledge and skills to real-life problems. CBL has been extensively used across academic fields such as law, business, accounting, and the health sciences, where empirical evidence of its benefits supports the method's popularity (Martin et al., 2019).

But regardless of its potential for addressing the industry's educational needs, CBL is rarely used as the core instructional approach in engineering courses beyond ethics (Martin et al., 2021). Instead, CBL is often relegated to a secondary role after other more common teaching strategies in engineering (e.g., Problem-Based Learning). In such instances, cases are often used to illustrate course contents, practice specific disciplinary methods, and expose students to a specific project (Jiménez et al., 2011; Korkmaz, 2011; Damnjanovic and Rispoli, 2014). We argue that useful as they might be, such implementations of CBL in CEM neglect the strategy's key strengths, which lie in its ability to exercise students' situational judgment, holistic thinking, and uncertainty management amid both typical and unique construction project situations (Fulk et al., 2017).

One of the factors that could explain the scarce use of CBL as the core instructional approach in CEM courses is that, in contrast to the disciplines that deploy their full potential, CEM faculty typically develop their whole professional careers in academia. Hence, they often lack relevant job site experience in construction-related working environments and are rarely active construction practitioners. This condition might limit their contextual situatedness and undermine their perspective-taking capacity and ability to be up-to-date with the industry realities, which are key to developing convincing cases and/or conducting engaging case-based discussions.

Despite this limitation, CEM faculty usually know the importance of course practicability and credibility for student learning and engagement. So, they frequently invite active industry practitioners as guest speakers and project evaluators to enrich their classes with real-world experiences. They also seek practitioners as liaisons for hosting construction site visits and as sources of documented cases, with varying success.

We argue that both practices (CBL and guest industry practitioners) contribute to student learning differently and that integrating active practitioners into a CEM course that uses CBL as the core teaching strategy might help deploy CBL's full potential. However, the synergies between CBL and Industry Practitioner integration have not been deeply explored in CEM education. Hence, there is scarce guidance on how CEM instructors can structure and implement a course in collaboration with CEM practicing professionals.

To fill this gap, we co-created, co-developed, and co-conducted a case-based CEM course in tandem with industry partners — formed by six major US construction companies, one design firm, and the University Facilities Management Department. The course was called "Construction industry workshop: Bringing theory to practice." Rather than emphasizing topics to be studied, the course comprised six typical CEM situations (the cases) to be addressed (See Appendix A), aiming to enhance student practical judgment and decision-making criteria. The industry partners participated in the identification of project experiences (which were relevant to a set of CEM learning goals), the development of teaching materials from these experiences, and the delivery and discussion of the cases during the academic semester.

We systematically gathered the cases' post-reflections and feedback from students, instructors, and practitioners in the course evaluations and conducted bottom-up thematic analysis (Fereday & Muir-Cochrane, (2006) to identify the emerging key lessons learned that may serve as guidance for the creation and implementation of similar CBL course initiatives in CEM. This paper describes the course resulting from that experience and shares the lessons learned.

The Case

Course Structure

The in-person course was designed to meet once per week for two-and-a-half hours. It was open to undergraduate civil engineering students who had already taken (or were currently enrolled in) the introductory course to CEM. The enrollment cap was set to 15 students. Every two weeks, self-selected teams of three students had to analyze a different case. The cases were designed and written by their real actors and the instructor before the semester began. Companies that had completed construction projects on grounds opted to select one of those projects as a case to attract students' interest, and the others opted to select a challenging one.

The selected projects spotlighted contending interests between the multiple actors and construction topics such as phasing, owner requirements, resource constraints, estimating, systems procurement, prefabrication, traffic and maintenance, CEM technology, contracts, commissioning, designer-builder collaboration, constructability reviews, site logistics, among others (see **Appendix A**).

The instructor scheduled monthly online meetings with some industry practitioners involved in each project to gather the information required to define the case learning goals and understand the project, e.g., context, complexity, constraints, stakeholders, conflicting interests, issues, challenges, and proposed solutions. The instructor wrote each case (six in total) based on the information provided by the practitioners and returned a draft to them, so they could fill out the missing information, improve the authenticity and accuracy, and provide the supplemental files needed to tackle the case. The cases ranged from five to eight pages, excluding any supplemental material.

The supplemental files sought to enhance students' case understanding and served as evidence to support their analysis and recommended actions. These included, among others, architectural and civil drawings, Requests for Proposals (RFP), Requests for Information (RFI), Baseline/Master Schedules, 4-D modeling videos, design drawings, contracts, commissioning plans, vendor bid proposals, site utility plans, and geotechnical reports.

The cases had two types of questions, open-ended and problem-solving. The open-ended questions sought to help each team understand the case and ignite class discussion. These questions focused on asking students to make an informed decision. On the other hand, the problem-solving questions asked students to evaluate two or three alternative solutions for the problem and recommend a course of action or propose a solution plan (see **Appendix A**).

Depending on the case questions, each team must submit either a written response, a PowerPoint presentation or both. In the written response, students addressed and discussed most of the open-ended questions and explained the reasons for any recommendation. In the PowerPoint submission, students addressed the problem-solving questions showing and explaining how and why a solution or approach was chosen over the others.

Furthermore, the following two assessment tools were used to monitor students' progress and learning and identify improvement areas after each case.

- **Post Reflections.** Acknowledging that real learning comes after thinking about what people saw and experienced, post-reflections were incorporated as an assessment tool to monitor students' learning process. The post-reflection form, which students must answer after each case discussion, was adapted from the one proposed by Golich et al. (2000). Some of the questions included were: What overall lessons do you take from this case? If any, which CEM technical or managerial skills have you learned or improved with this case? If any, what were the most challenging aspects of this case study? What helped to improve your learning, and what hindered it? What is your goal for the next case?

- **Self-Evaluations.** Two self-evaluations were used to assess students' participation during i) case preparation and ii) class discussion. The former was included, given the importance of being an effective team member in the workplace, and the latter, to motivate the interactions between the student groups and between students and industry practitioners. The two forms were taken from the ones Golich et al. (2000) proposed.

Course Implementation

The cases were released to students every two weeks during class time. Despite the course being set to meet once per week, the instructor met with the students every two weeks when the practitioners came to the classroom — the day a case was released, there was no whole-class meeting scheduled (see Figure 1). Instead, students were encouraged to meet with their teams to review the case materials, post any questions, or request additional project documents they may need moving forward with the analysis. This means students had one week to read, assess, and discuss the case study with their teams before the class discussion.

The following week after receiving the case, all teams met (in person) with the industry practitioners and the instructor to discuss their analyses and responses to the case and hear how the real actors tackled the project challenges along with "the rest of the story." The class flow (sequence) varied depending on the combination of the case questions, as outlined below:

- **A case including open-ended and problem-solving questions**. First, students discussed the open-ended questions with the case's real actors at a round table for about 50 to 60 minutes. The discussion atmosphere was informal and relaxed. The instructor moderated the discussion by fostering a candid conversation between students and practitioners while addressing the open-ended questions. Then, each team presented its solution plan or recommended action to the practitioners within 15 minutes. After each presentation, practitioners gave feedback to the students and asked them questions about their proposed solutions. Finally, in the last 30 minutes of the class, the case's real actors presented their approach to solving the problem, shared some lessons learned, and addressed any last-minute questions students may have.

- **A case including only open-ended questions.** Most of the class time was devoted to discussing students' insights about the case questions with the case's real actors in an informal setting like the one described above. The informative discussion lasted about 80 minutes, and either the instructor, practitioners, or students asked to follow–up questions. Then, in the last 30 minutes of the class, the practitioners highlighted parts of the case that were particularly challenging during the project. Some guests prepared a presentation for the students, and others opted to continue the informal discussion.

- **A case including only problem-solving questions.** Most of the class time was devoted to students' presentations (20 – 25 minutes per team). Each team presented its solution plan to the case's real actors and recommended a course of action. Once all teams presented, the practitioners gave each team feedback highlighting any additional constraints/technical details that students did not realize would be problematic when analyzing the case. Then, in the last 40 minutes of the class, the guests explained how they handled the problem, established priorities, made tradeoffs and decisions, and addressed any last questions. Given the need to use visual aids, all guests prepared a PowerPoint presentation, so students had a better grasp of the complexities of the case.

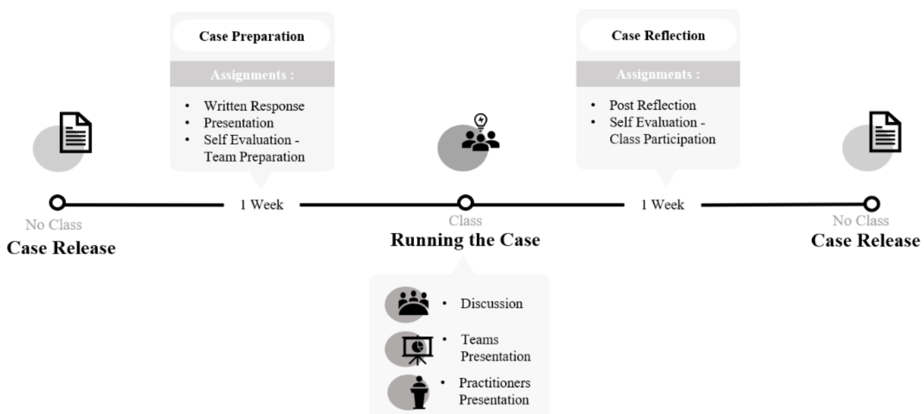

Figure 1**.** Course Flow

Since the class flow differed for each case, the instructor sent the practitioners an agenda outlining the class's main moments. Additionally, the instructor met with the industry practitioners before the case discussion to go over the class logistics. It was essential to clarify their roles in the class discussion since students should have the space to express their thoughts and analysis without the guests giving them all the answers at first. The instructor printed a copy of the agenda and case for each guest and gave them an additional blank sheet to take notes; meanwhile, students made their interventions in the class.

Lessons Learned

Structuring the Course

Avoid monotony by design. A 2.5-hour encounter proved to be sufficient to achieve the learning goals of each case. However, it can turn monotonous if you do not plan to incorporate different moments or short-sprint activities into each class session. Students reported being more engaged when having different activities (e.g., 2-way presentations, discussion time, Q/As, and intra-group and whole-group activities) in one session.

Build students' confidence by planning the cases' order. Students reported feeling overwhelmed in the first couple of cases when they had to make complex decisions with insufficient information and limited experience. Consider adjusting the difficulty of the cases incrementally to match their learning curve.

Opt for smaller class sections and student teams. Instructors and co-instructors agreed that a small class size was vital in ensuring that all students could voice their opinion and boosting social safety so that everyone (including industry practitioners) could feel comfortable presenting and participating in the discussion. From the student perspective, having a team of three students balanced individual workloads and promoted equal contribution, preventing "one or two hide and don't do their share."

Include team preparation time deliberately in the formal class schedule. When students' schedules conflict, they tend to rely on individual preparation only, and team preparation time is at risk. Students applauded the use of synchronous class time to allow teams can meet consistently.

Release case materials as early as possible. This practice allowed students to review the material individually and then meet with their team during class. They were also able to "understand the situation first," identify the technicalities they are unfamiliar with, and then "invest more time brainstorming alternatives, agreeing, developing the selected solution, and finding the best way to communicate it with their team members."

Prepare to switch teams occasionally. Although student participants did not experience this directly, many suggested that changing teams in future course iterations would benefit their learning experience. They were interested in learning from others' "industry experience and knowledge." Plus, this is how it happens in real CEM projects.

Start by focusing on cases with a documented "path of solution." The availability of construction documentation and visual aids is a restrictive factor in deciding whether to use a project for a case. Most partners kept a record of the "definitive solution" of their projects but not of the alternatives considered nor iterations conducted. Remember that construction documents are not usually readily available for didactic application. Presentations made for clients proved to be effective communicators of the project situations to students.

Prefer projects that are familiar to students. Credibility turns out to be the most engaging factor for students. The more "real" the situation is perceived, the more engaging the case. Moreover, students are more engaged, intrigued, and invested when the cases are based on campus projects since it is easier for them to relate to the context.

Incorporate tasks that resemble actual construction tasks. The more CEM-representative the task, the more valuable the students perceive it. That being said, avoid asking for repetitive tasks even if they resemble actual CEM practice (e.g., checking all geotechnical borings in case #5). Students are more engaged when cases incorporate open-ended questions and unique problems since they allow them to explore different routes and cultivate more discussion within their groups. Having open-ended problems guarantees that every group will propose something different, and they can learn from what other groups considered and did not.

Help students navigate the supplemental material. As discussed before, achieving credibility often requires using actual construction documents. However, students get overwhelmed if they are required to face extensive pieces of data without knowing where to start or to focus. Cultivate data literacy by helping students navigate the supplemental material. To do so, deliberately include cues in the narrative or notes pointing to a specific section or resource.

Invest time in adapting or developing resources that help students visualize the case situations. Helping students get a clear picture of what is going on in the project is of paramount importance for the case's success — especially with an inductive approach, not only as understanding the situation is the basis for a good analysis but also to avoid students overwhelming and frustration, given their lack of experience and exposure to construction day to day issues. Hence, make sure you devote a significant portion of your preparation time to developing, in partnership with industry practitioners, visual aids to increase clarity and student understanding. Take advantage of the BIM and 4D simulations available for the case since these can be useful to illustrate initial project conditions or construction sequences.

Course Implementation

Get used to your new facilitator role. The role of the CBL instructor is to be a facilitator or mediator of the interaction between students and industry practitioners. The instructor must empower both to participate in the discussion actively, provide feedback and ask follow-up questions. Although this role may be diminished during the class, the instructor is the real architect behind orchestrating a meaningful adequate teaching-learning environment for all the case participants.

Open discussions with factual questions. It is difficult for students to understand what happens in a construction project when they are unfamiliar with specific construction means and methods and have not spent much time at a job site. Therefore, students must have the chance to clarify the case context and situation with the industry practitioners before starting the case discussion.

Bring different perspectives and voices. Hearing the points of view of the case from different stakeholders (owner, designers, subcontractors, and contractor) allows students to gather more insight into real-life scenarios that these industry practitioners face daily. The different perspectives help students to solidify and reaffirm their thoughts about the case, clarify some predetermined misconceptions, and identify challenges they did not realize would have been problematic. The presence of the cases' real actors also motivates students to perform at a higher standard.

Share first-hand experiences and memorable facts and stories. Students learn better when the practitioners give them first-hand experience in handling problems in the construction industry and provide them with feedback. Additionally, humor and curious facts about the case exhibited during the discussion by the practitioners improved students' memorability and learning.

Foster a networking space. The class setup offers students a great opportunity not only to get some construction industry experience but also to network with potential future employers. Encourage students to learn more about the company and practitioners participating in each case and prepare questions for them in advance to interact more with them after the class discussion. Noteworthy, when applying for engineering roles with general contracting companies, some of whom were guests in the class, students felt much more comfortable and informed going into these interviews.

Use reflections as a learning tool. After listening to the train of thought and seeing how practitioners reached the best approach for all the stakeholders, the post-case reflections forced students to continue thinking about the case, as often, after a project is over, they will just put it out of their minds. By reflecting on how they can improve their case analysis, students clear up their learning, reaffirm the main takeaways/lessons learned from the case, and prompt them to think about how they can do better in the following case.

Conclusion

This paper analyzed the experience of developing and teaching a CBL course in CEM with a diverse group of industry practitioners and synthesized 17 lessons learned (11 relative to course structure and 6 to implementation). These lessons may guide those interested in fully exploiting CBL through the involvement of the cases' real actors (active industry practitioners) to build students' ability to make decisions in real-world CEM scenarios. It also explored the potential synergies of CBL and the typical teaching practice of bringing industry practitioners to CEM courses: The classroom power distribution became more balanced since the "instructor" needed to transition to a discussion "moderator /facilitator" role. This empowered students to become more active learners and practitioners to become true agents of students' education. The presence of the cases' real actors (industry practitioners) in the CBL classroom increased the cases' credibility, students' confidence in the applicability of the knowledge that was being constructed, introduced them to a variety of construction-related topics that go beyond the traditional CEM curriculum, increased the understanding of actual CEM practice and the different career paths available, provided opportunities to expand students' professional network, and motivated students to do their best to make a good impression. Students had the opportunity to contrast their proposed approaches and solutions with the ones proposed by those with first-hand experience and in the exact situation under consideration. Thus, similarities gave students confidence in their problem-solving approaches, whereas differences proved to be a source of further discussion and direct feedback. Although the implementation in the classroom of CBL combined with industry practitioner involvement may require significant planning on the instructor's side, the reported benefits make the effort worth it.

References

Damnjanovic I, and Rispoli, J. (2014). Case Study Narrative in Teaching Construction Project Management: Earned Value Method Examples. Pract. Period. Struct. Des. Constr., 2014, 19(1): 41-49. https://doi.org/10.1061/(ASCE)SC.1943-5576.0000192

Fereday, J., & Muir-Cochrane, E. (2006). Demonstrating Rigor Using Thematic Analysis: A Hybrid Approach of Inductive and Deductive Coding and Theme Development. International Journal of Qualitative Methods, 5(1), 80–92. https://doi.org/10.1177/160940690600500107

Fulk, B., Ghahari, S., and Hastak, M. "Case study and apprenticeship pedagogy for training construction engineering students," *2017 IEEE Frontiers in Education Conference (FIE)*, 2017, pp. 1-6, https://doi:10.1109/FIE.2017.8190570

Golich, V. L, Boyer M., Franko P., and Lamy S. (2000). The ABCs of Case Teaching. Pew Case Studies in International Affairs.

Martin, D. A., Conlon, E., and Bowe, B. (2021). Using case studies in engineering ethics education: the case for immersive scenarios through stakeholder engagement and real-life data, Australasian Journal of Engineering Education, 26:1, 47-63, https://doi.org/10.1080/22054952.2021.1914297

Jiménez, J., Pellicer, E., and Yepes, V. Teaching and learning using a case study: application to a Master Degree in Construction Management. Procedia - Social and Behavioral Sciences, Volume 15, 2011, Pages 696-702, ISSN 1877-0428, https://doi.org/10.1016/j.sbspro.2011.03.167.

Korkmaz S. (2011). Case-Based and Collaborative-Learning Techniques to Teach Delivery of Sustainable Buildings. Journal of Professional Issues in Engineering Education and Practice, Volume 138 Issue 2. https://doi.org/10.1061/(ASCE)EI.1943-5541.0000090

Safapour, E., Sharareh K., and Piyush, T. (2019). "A Review of Nontraditional Teaching Methods: Flipped Classroom, Gamification, Case Study, Self-Learning, and Social Media" *Education Sciences* 9, no. 4: 273. https://doi.org/10.3390/educsci9040273

Appendix A

Case	Problem	Examples of Question Types		Case Practitioners Participants
#1	A significant delay in an enabling project before the start of construction led the team to reconsider their phasing approach to completing the project since the schedule and budget needed to remain on track.	Open-Ended	○ Who bears the responsibility of solving this issue and why? ○ How will this issue impact the project scope, schedule, and budget?	Owner (FM)*: ○ Supervisory Team Leader Contractor: ○ Senior VP**, Project Executive, Project Manager
		Problem-Solving	○ Analyze emerging solution alternatives, evaluate how they impact the project schedule and budget, and recommend a preferred solution pathway.	
#2	In a multi-prime contract, a disagreement between the designer and the mechanical contractor arose because of fluctuating owner requirements and the ultimate effects these changes had on the design and construction of the building's HVAC system and the Net-Zero goal.	Open-Ended	○ How did the multi-prime contract benefit or affect this project's bid and design phases? ○ Do you agree with the owner's decision to have the firm as the designer and commissioning agent of the project?	Design Firm: ○ VP, Project Engineer, Commissioning Agent
#3	Because the project was a partial renovation with an existing structure, the overall construction schedule was compressed. Envelope and finish materials were needed sooner after the commencement of construction.	Open-Ended	○ How should the owner weigh early commitment of funds and early decisions against a potentially longer overall construction schedule?	Contractor: ○ Preconstruction Leader
		Problem-Solving	○ Evaluate different bid proposals and recommend the contractor a trade partner for completing the curtain wall system. ○ Perform a cost-benefit analysis of bathroom pods vs. field build.	
#4	Because the number of available beds during the renovation of six four-story buildings directly impacts the owner's revenue, the client wants the contractor to finish the project one year sooner than the RFP timeline.	Problem-Solving	○ Recommend the contractor how to best pair up the buildings to finish one year sooner than the RFP timeline keeping in mind the owner, client, and contractor constraints.	Owner (FM): ○ Senior PM*** Contractor: ○ Senior VP, PM, Project Engineer
#5	During a preconstruction site walk, the owner team noticed the presence of surface rocks on the site. The contractor has now to review the geotechnical report and analyze the risks associated with installing the structural foundations and utilities, given the presence of rock and groundwater.	Open-Ended	○ If the team had to hit the rock, what would be the best procedure to remove it (with the neighbors and budget in mind)?	Contractor: ○ VP, Project Manager
		Problem-Solving	○ Develop a preliminary site logistics plan addressing staging and potential impacts on surrounding neighborhoods and businesses.	
#6	Given the county constraints regarding installing a pedestrian walkway over one of the county's busiest thoroughfares, the contractor had to propose the prefabrication, transportation, and installation of the complex structure in one week.	Open-Ended	○ How would you sell the idea to the county, highlighting the benefits to the public? ○ How can VDC models and reality capture identify conflicts and prevent risks regarding the installation of the bridge?	Contractor: ○ VP, VDC Leader ○ Construction Executive
		Problem-Solving	○ Develop a Maintenance of Traffic plan for the move and installation of the bridge.	

* FM: Facilities Management; ** VP: Vice President, *** PM: Project Manager

Sense of Belonging: Exploring the Narratives of Latinx Construction Education Students

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The demand for construction managers (CMs) in the United States continues to increase. Being predominately white and male-centric has not helped reduce the challenge that comes with the need for more CM professionals. This research explores the lived experience and supports systems Latinx students experience in construction education at a predominately white university utilizing the Latinx critical race theory (LatCrit) lens. Four first generation Latinx undergraduate students - two Latino (male) and two Latina (female) - participated in this study, and a semi-structured interview protocol that the Institution Review Board (IRB) approved was utilized. All study participants shared insights and reflected on their "sense of belonging" as construction education students at a predominantly white university. The female participants, in particular, explored how being a woman with limited construction work experience created a barrier to their sense of belonging. "Sources of support" like participating in a learning community, counterspaces, professor support, group involvement, and volunteer opportunities helped to boost individual morale and sense of belonging.

Key Words: LatCrit, Sense of Belonging, Gender, Construction Management, Women

Introduction

University-educated construction managers (CMs) are in high demand in the United States (U.S.), and higher-than-average industry demand for CM professionals is projected to continue through 2031 (BLS, 2022). Like other STEM professions, women and underrepresented racial/ethnic minorities (URMs) are unrepresented in the CM workforce when compared to their participation rate in the U.S. workforce overall (BLS, 2022). Additionally, evidence suggests women and URMs are underrepresented in university construction education programs and that the academic success gaps between non-Latinos and Latinos in construction education mirror overall higher education trends (Burgoon & Elliott, 2022; Excelencia in Education, 2019).

While previous research has suggested the possibility of academic success gaps between Latino and non-Latino students in CM education, the reasons for these gaps remain largely unexplored. Furthermore, while numerous researchers have addressed factors that propagate the under-representation of women in construction education, research exploring the perceptions of Latina women and other women of color in construction education is minimal. As such, this study aims to explore the challenges and support systems of Latinx students enrolled in construction higher education. Specifically, this study will utilize a critical framework to explore four Latinx students' sense of belonging. This study also adds to the limited body of knowledge surrounding critical inquiry and Latinx students' sense of belonging in architecture, engineering, and construction (AEC) education.

Theoretical Framework

Latinx critical race theory (LatCrit) provided a theoretical framework for part of this study. LatCrit is a framework that focuses on individuals' lived experiences as a means of identifying patterns and practices of racial and ethnic exclusion (Villapando, 2004). Emerging from the legal scholarship of critical race theory in the U.S., LatCrit positions Latinxs at the center of analysis within the broader context of oppressive social systems. Furthermore, the theory encourages participants and practitioners to take action to disrupt oppressive systems (Delgado & Stefancic, 2001). Within the higher education setting, Villalpando (2004) outlines five foundational tenets of LatCrit. These tenets are: 1) the existence of racism in the U.S. education system and the importance of intersectionality in understanding oppressive societal systems; 2) the importance of challenging dominant ideologies regarding 'race neutrality,' 'colorblindness,' and 'equal opportunity' in higher education; 3) the role of social justice practice in creating more equitable educational systems; 4) the recognition of experiential knowledge as a legitimate basis for understanding social inequities; and, 5) an emphasis on the effects that historically inequitable policies and practices in higher education have on Latinx students.

Paramount to LatCrit for this study is the utilization of storytelling (and counter-storytelling) in constructing experiential knowledge. Counter-storytelling confronts dominant narratives and can support URM communities in at least four ways: creating a greater sense of community, challenging long-held narratives and beliefs, helping individuals feel less alone, and providing a framework for deriving a more meaningful existence (Solorzano & Yosso, 2001). LatCrit provides a relevant lens for this study because: 1) all participants self-identified as 'Mexican' - independent of whether or not they were born in the U.S. or Mexico; 2) participants were enrolled in a predominantly white institution (PWI) in the U.S.; and 3) Latinx individuals, especially women, are underrepresented in the CM profession and education (BLS, 2022).

In addition to exploring the stories and counterstories of Latinx students from a critical perspective, the authors felt it is also important to examine the systems and organizations that have supported the student participants during their academic pursuits. As such, two umbrella questions guided interviews and analysis:

1. What challenges has the student experienced in CM education – including challenges experienced at the university more generally
2. What organizations, systems, or individuals have provided the students support while pursuing their CM degree

In exploring these guiding questions, it is important to remember that from a LatCrit perspective, each participant's lived experience is considered legitimate experiential knowledge. As such, all participants are uniquely qualified to speak on their sense of belonging in construction education. Furthermore, while not generalizable, accepting individuals' narratives as legitimate knowledge could assist CM educators and administrators in areas ranging from student-faculty interactions to admissions policies (Darder, Baltodano & Torres, 2003).

Methodology

This study focused on the first-person narratives of two (2) Latina and two (2) Latino undergraduate students majoring in construction education. Perspective participants were solicited through an email from the Latino Cultural Center (pseudonym) – the university's Latino support office. Participants took part in individual, in-person, semi-structured interviews, which ranged between 53 and 97 minutes. Interviews were audio recorded and subsequently transcribed for analysis. Institutional Review Board approval was granted before beginning this study.

This study was bounded to first-generation Latinx undergraduates enrolled as construction education majors at a single public university in the Rocky Mountain region of the U.S. All participants were enrolled in junior or senior-level construction education coursework at the time of the interviews. Participants were asked to identify their salient identities and to select pseudonyms to maintain confidentiality and anonymity. These are identified in Table 1.

Table 1

Description of Participants' Identities (Self-identified)

Pseudonym	Preferred Ethnic Descriptor	Gender
Isabella	Mexican	Female
Osiris	Mexican	Male
Wade	Mexican	Male
Yatziri	Mexican	Female

Findings

Multiple themes were identified during analysis and are supported with direct lines by the participants. For this study, the authors have chosen to focus on students' perceived sense of belonging in construction education (and, by extension, the university) as the primary theme for evaluation. All participants acknowledge that a sense of belonging has been an essential aspect of their secondary and post-secondary education journey.

Sense of Belonging

Goodenow (1993) defined "sense of belonging" as the extent to which an individual feels accepted, respected and supported in their social environment. As first-generation students that attended racial/ethnic diverse high schools, three of the student participants expressed feeling a sense of other while attending the predominantly white university. This article uses "sense of other" to suggest the opposite of sense of belonging (Goodenow, 1993). For example, as told by Wade in describing his first year:

> Honestly felt like I stood out. I know I don't look it, but even the feeling that when we first came … [to the university] and into the CM program, there wasn't very many Hispanics or Latinos and everything like that. So, I didn't really have anyone to really relate to at that

> point. The only other Hispanic I knew was the guy that was here, and I only talked to him briefly. So I didn't really feel like the part; I felt like I stood out.

For Osiris, he stated that he never felt "discriminated against" or "talked down to" in the CM program, but he still thinks that "some people will notice the difference in appearance." As part of the larger campus community, Osiris, a junior, had recently begun attending the Latino Cultural Center occasionally because:

> I get homesick. And the environment that I know at home is, you know, speaking Spanish and seeing people who look like me. And, you know, walking around campus, you don't see that very much. So, I go there sometimes just to relax. It's a small environment. I like, you know, I feel like I'm refueling myself; recharging my like social battery in a way. And a lot of my friends hang out there too, and more Hispanics… I like seeing people who resemble me and come from different backgrounds sometimes.

Isabella explained how coming to a PWI was a different experience than what she was raised with:

> Coming to college, I realized the difference it is here from [name of hometown]. But growing up, I thought I lived like a normal life. You know, it's like my mom and dad, speaking Spanish and English, because everybody's Hispanic, like, mostly everyone is Hispanic. So it wasn't like, there's a difference from what I see [at home] to other places. But then, coming to college, I realized, whoa, like, it's way different than what I realized.

While all participants felt supported in the CM program overall, they also felt that they lagged behind most of their colleagues when it came to construction work experience. Wade stated: "Everyone came from a family that had a super strong background in construction and like their dads run something, or they've been in it their whole life. Or, you know, just things that I couldn't relate to. My family didn't really have a construction company." Osiris expressed a similar sentiment:

> I think it makes it a bit, a little bit more challenging here as a CM major, because like, coming in freshman year to college, I was taking classes and there were a lot of people who had like a lot of construction experience. You know, there are people who had like families who like had small companies. There were people there who were already working for their companies. And I was just there, like, this is all brand new to me. And that kind of made me feel like I was behind everybody.

Yatziri and Isabella expressed similar thoughts (which will be further explored in the next section) but felt a great sense of other because they are women with construction limited experience.

Gender and Experience

Both Yatziri and Isabella expressed how being a woman – particularly a woman with limited construction work experience - affected how they interacted with classmates, faculty, and potential employers. Discussing her interaction with "guys" in classes, Yatziri stated that while she's never had anything "bad happen" and that her "guy" classmates were regularly "supportive" and "think it's kind of cool that I'm like one of the like few girls that are actually in the program," she also acknowledges that "sometimes you can feel like the vibe, or like the energy, that like someone gives off that they don't really appreciate your presence…"

She also provided a specific example of when she was treated differently because she is a woman:

> In the lab, sometimes…they [male classmates] kind of just take over sometimes. Like they want to do it because they think I'm not gonna do it right. And at that point… I'm not gonna like stand there and be like, 'no, let me do it.' I just kind of, like, let it happen, you know, like, 'okay, if you want to do the work.'

When asked why she felt male colleagues would take over, she stated:

> I think it's because I'm a girl, okay… like, when I had to carry something that, like, they kind of sometimes ruin it. Like, you know, it's kind of like being a gentleman. They'll be like, 'I'll carry that,' and it's like, okay, like, 'you can carry it,' but like… 'I can carry it too you know.' So it's just kind of making me feel like a girl all the time.'

While recognizing that her male classmates were likely trying to be "gentlemen," she ultimately stated: "sometimes it's really annoying that they don't let me do things for myself."

Concerns around how she is perceived as a woman also affected Yatziri's desire to seek assistance from faculty instructors. As described by Yatziri:

> I feel like I'm definitely more scared to, like, go and talk to professors. I don't like going to office hours. I hate it! I don't know, I don't like it just because I feel like, I'm a girl. And like, I'm already, like, asking for too much help already…the times that I have gone. They're very helpful. But I just feel like, I like bother the professor. It's like, oh, like this girl, you know.

Similar to Yatziri, being a woman with limited construction work experience in classes with "guys" who have more construction work experience has been challenging for Isabella:

> It is definitely hard, because, like, you have the guys. Like a majority of the guys in class are guys [men]. And they're tall and everything. It's kind of scary…a lot of them have experience [construction work experience], so they know what they're talking about. And me, coming in with nothing of experience. It's kind of hard, like, feeling committed to the [CM degree] program or thinking I could do it and finish it.

She went on to describe the way she modified her appearance to better fit in during her first year in the program:

> I think it affected me, physically, which is kind of weird, because I told myself like, 'I can't dress girly.' Like I had to dress, not tomboyish, but, you know, like, not girly, so they take me serious. So, I remember freshman year. I wouldn't get ready...I don't know how to explain it. But I'd be like, 'some of the will guys to take me serious,' you know?

Despite completing two years as a construction major, Isabella admitted that she was planning to switch majors to business administration. When asked why she explained:

> So, I think a lot of it has to do with not knowing a lot about construction. Like, I definitely have learned a lot more but not having that experience has pushed me to have, like, the thought, "is this right for me"? "Am I doing what I'm supposed to be doing"? "Am I using the skills I have, and something that will help me out in the future"? And sometimes I feel scared, I guess like, if I do stick to construction, like once I go out there, like I don't know

> anything, I don't know anyone, and I'm a woman in construction. So, I think that's the kind of scary part which has pushed me to [majoring in] business.

Sources of Support

While participants identified numerous challenges to their sense of belonging as CM and university students, they also identified numerous support systems, communities, and individuals that bolstered their sense of belonging.

As previously mentioned, Osiris found support and felt like he is "recharging" and "refueling" by socializing at the Latino Cultural Center and had recently joined a fraternity and CM club. However, attending after-hours events was difficult because the: "last shuttle leaves at like 6:40."

Like Osiris, but even more so, Isabella found that her first-year experience in a learning community, which notably included volunteering: 'helped a lot." More generally, volunteering was a way for Isabella to learn and feel more connected. Specifically, she volunteered with the Latino Cultural Club, and Habitat for Humanity to help: "families who need a home and to learn about construction." She also participated with the Women in Construction club her first year which allowed her to see that "women can succeed and be the boss as well." Isabella also stated that she would be be willing to stay in CM if a faculty member would help her to get an internship. Specifically, she said, "I think a lot of the me moving into the business major is being scared of not getting an internship or not having work experience." Still, at the same time, she showed reluctance to individualized support as: "other students already have internships and work experience. So like, I should be able to too."

Wade actively sought mentoring during his first year through the Latino Cultural Center to help him: "adjust and learn how to do things in college." During subsequent years, Wade joined a CM competition team and took a leadership role in a CM club. Pivotal in his decision to join a team and take on a leadership role was a single professor who: "convinced me to join the sustainability team and, you know, when elections came, he pushed me more towards actually taking your position in the club." When asked whether the professor's Latino identity had anything to do with his perception he stated it: "absolutely had nothing to do with his background, ethnicity, whatsoever. Just [professor's name] as a person."

Yatziri found support through the women in construction program before even attending college:

> So Mr. [high school teacher's name], he did women in construction. And he brought a bunch of people. And he brought [names of two faculty/staff women from the university's construction program] from the program here to like, go speak to us girls, about you know, possibly doing construction management. And I think back then, what like, I think it was like 5% or 6% that of the girl ratio to guy that was doing the program. So I was like, 'wow, like all these other like, ladies seems like so bossy and I was like I really want to be like them.'

The Latino Cultural Center also provided Yatziri with: "connections that I do have today." Paramount in this was the connection she made with the center's director – who also serves as her scholarship advisor:

> She [the program director] would tell me about like events going on, like opportunities organizations that I could join, you know. When I was looking for a job, like I went up to her

> and I was like, [director's name], like, I need a job and I don't know what to look for. And she like, kind of helped me guide me through that, too.

The same professor that Wade mentioned, Yatziri mentioned too.

Discussion

Viewed through a LatCrit lens, the students' perspectives provide counterstories and insights to dominant narratives. As described by all participants, counter-spaces, in this case, the Latino Cultural Center and racially/ethnically diverse learning communities, provided students with various forms of support as they transitioned to life at a PWI. As described by Yosso et al. (2009), counterspaces can be both social and academic and may help Latinx students to cultivate a "sense of home and family, which bolsters their sense of belonging and nurtures their resilience ." (p. 677) While learning communities provided first year support for two participants, the Latino Cultural Center provided different forms of support for all participants. For Wade, support came through mentorship from others during his first year of college, while Isabella's interaction with the program offered her opportunities to provide volunteer service to others. For both Osiris and Yatziri, the social interactions they experienced at the Latino Cultural Center were essential to their well-being and sense of belonging on campus.

While only mentioned by the two women participants, intersectionality played a role in the lived experiences of Isabella and Yatizi. While not generalizable, Isabella's and Yatizi's experiences align with the experiences of other Latinas in white male-dominated fields and shows the importance of proactively creating learning environments where students with diverse experience levels and backgrounds can continue to grow and develop (Lara, 2017). Given the specific comments mentioned by the participants, CM educators could evaluate how much emphasis they place on students' construction work experience in the classroom, as this may create perceptions of superiority and inferiority among students and ultimately disincentivize less experienced students from participating in class discussions or seeking faculty support.

By exploring the sources of support for individual students, CM programs and educators can begin identifying sources of support for Latinx (and potentially other URM) students. While some of these supports could be substantial, based on the size of the CM program and university (e.g., a CM-specific learning community), others could be implemented with little to no financial resources. For example, mentorship programs and CM clubs (specifically those aimed at supporting women or URM students) could yield positive results (Lavorico, 2018).

Conclusion

In conclusion, construction education programs are morally obligated to create a more inclusive and supportive environment that promotes a sense of belonging for all students – specifically those traditionally underrepresented or marginalized. Exploring student stories and viewing them through a LatCrit perspective could drive long-term change for those Latinx, and other URM students, who feel a decreased sense of belonging by challenging dominant narratives and helping students feel less alone in their experiences (Solorzano & Yosso, 2001).

References

Bureau of Labor Statistics (BLS), U.S. Department of Labor, Occupational Outlook Handbook, Construction Managers, at https://www.bls.gov/ooh/management/construction-managers.htm (visited October 05, 2022)

Bureau of Labor Statistics (BLS), U.S. Department of Labor, Employed persons by detailed occupation, sex, race, and Hispanic or Latino ethnicity athttps://www.bls.gov/cps/cpsaat11.htm

Burgoon, J., & Elliott, J. (2021). Evidences of Opportunity Gaps in Construction Management Education. EPiC Series in Built Environment, 2, 559-567.

Darder, A., Baltodano, M., & Torres, R. D. (Eds.). (2003). *The critical pedagogy reader*. New York: RoutledgeFalmer.

Excelencia in Education (2019). Latinos in higher education: Compilation of fast facts

Goodenow, C. (1993). The psychological sense of school membership among adolescents: Scale development and educational correlates. *Psychology in the Schools, 30, 79-90.*

Lara, H. (2017). Latinx Students in STEM Education Research: A CRT and LatCrit Analysis of NSF Funded Projects.

Lavorico, L. (2018). Creating and Implementing an Industry Mentorship Program Within the Women in Construction Club.

Melendez, M. (2017). A Phenomenological Study of the Lived Experiences of Latina Engineering Students at a Community College: Intersection of Race, Gender, and Class. *ProQuest LLC*.

Solorzano, D. G., & Yosso, T. J. (2001). Critical race and LatCrit theory and method: Counter-storytelling. International Journal of Qualitative Studies in Education, 14(4), 471–495.

Villalpando, O. (2004). Practical considerations of critical race theory and Latino critical theory for Latino college students. New directions for student services, 2004(105), 41-50.

Yosso, T., Smith, W., Ceja, M., & Solórzano, D. (2009). Critical race theory, racial microaggressions, and campus racial climate for Latina/o undergraduates. *Harvard Educational Review*, *79*(4), 659-691.

Optimizing Project Demolition Using Integrated Building Information Modelling (BIM) and Lean Construction Approach

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Highest amount of Construction and Demolition (C&D) wastes are produced during the demolition phase of building lifecycle stages, which results in significant loss of natural resources, and exhibits adverse environmental impact globally. BIM processes and Lean principles have been used in improving demolition waste management on the individual aspect basis; however, the synergies of both these systems are not fully explored especially during demolition stage. This paper focuses on alignment of integrated Lean-BIM processes to optimize the waste reduction aspect during project demolition phase. The method involves (1) developing 3D BIM demolition model using a selected real-time demolition project as a case study, and (2) establishing a client's need-based model of salvaged elements, using the developed 3D BIM model, for deciding the destination of demolished material as a Lean Construction approach. This approach can be expected to improve the rate of reuse and recycle of demolished material, that can ultimately lead to saving natural resources by sending less material to landfill/disposal sites.

Key Words: Demolition, Building Information Modeling (BIM), Lean Construction, 3D Model

Introduction

The Construction and Demolition (C&D) waste is defined as a mixture of debris materials generated from construction, rehabilitation, renovation, and demolition processes. The construction industry has been severely confronted with its negative economic, environmental, and social impacts throughout the whole building life cycle (Shen, Tam, Tam, & Drew, 2004). The key problem of C&D waste is the generation of highest waste rate compared with other industries (Yuan & Shen, 2011). Developing the strategies to manage C&D waste is becoming urgently required by all the stakeholders involved in the process, all over the world. Some of the current research highlights that waste minimization regulations do not sufficiently incentivize owners, contractors, and subcontractors to take preventive actions to eliminate waste during the building demolition stage (Karaz, Teixeira, & Rahla, 2021). The intensification of adoption of Building Information Modelling (BIM) has given a significant push to the implementation of Lean principles within the construction industry (Karaz et al., 2021). With the revolution going on in the industry for managing the demolition waste generated from a project, the BIM practitioners started recognizing Lean strategies as underlying processes for various BIM usage implementations. There has been an increase in the interest of visual components of BIM and Lean concepts, with multiple notable studies investigating the possibilities of Lean and BIM interactions (Sacks, Koskela, Dave, & Owen, 2010a). Recent research on BIM and Lean Construction shows that there is a need of significant synergy between these two areas. This paper discusses the alignment of integrated Lean-BIM processes to optimize the waste reduction aspect during project demolition phase. It is a notable point of discussion that the BIM-Lean synergy is not only limited to the design phase, as it might seem to be limited to, but also extends over the whole project life-cycle phases with the rapid advent of multi-dimensional BIM capabilities (Lean Construction Blog, 2022).

Impact of BIM in Project Demolition Phase

Building Information Modeling (BIM) is the process and practice of virtual design and construction throughout the project lifecycle phases (Eastman, Eastman, Teicholz, Sacks, & Liston, 2011). According to the National BIM Standard, Building Information Model is "a digital representation of physical and functional characteristics of a facility and a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle from earliest conception to demolition" (NBIMS, 2010). Contributing evidence has been found regarding the capability of BIM functionalities in providing the end-of-life scenario analysis for a project. For an example, the researcher has demonstrated how the deconstruction and demolition plans can be obtained from a project BIM model (Akinade et al., 2017).

Over the last several decades, the significance of demolition and renovation (D&R) work has grown to a considerable extent and accordingly the volume of D&R debris disposed to the landfills, particularly in big cities, have increased throughout the world (Li et al., 2020). Quantitative waste prediction has been a crucial subject for managing the demolition waste, which can enable the contractors to critically plan and manage the waste generation processes and to plan waste control strategies in the demolition stages. A considerable amount of literature provides a picture of the latest developments in providing BIM-based tools for construction and demolition waste (CDW) management (Nikmehr, Hosseini, Wang, Chileshe, & Rameezdeen, 2021a). BIM-based tools and technologies for dealing with CDW throughout the whole life cycle of construction have been investigated at various levels. Research findings show that although various BIM-based technologies are closely associated with CDW, many of which only have focused on the design and construction phase and the problem of CDW in post-construction and demolition phases has received little attention (Nikmehr, Hosseini, Wang, Chileshe, & Rameezdeen, 2021b). In the current scenario, the available BIM tools and technologies are found to be lacking when dealing with project demolition waste aspects and are weak in theoretical accuracy (Marzouk, Elmaraghy, & Voordijk, 2019).

Since it is hard for contractors to come up with the 3D view of project from different traditional 2D drawings, the visualization capacity of BIM provides a better understanding of what the final product may look like. A common thread runs through all BIM software, i.e. Parametric Modelling, which is a characteristic that enables visualization of the aesthetics and functions of buildings (Sacks, Koskela, Dave, & Owen, 2010). This feature has aided the adoption of BIM across the construction industry to improve project delivery and building performance. Similarily, during project demolition phase, architects and designers can provide rendering and walkthroughs to better communicate the concept of project demolition sequential steps to the customer or end user (in case of salvaged material buyer) using BIM based 3D model. (Marzouk, Elmaraghy, & Voordijk, 2019b). Furthermore, virtual mock-ups of sequential demolition steps for a building can be provided to the owner and other stakeholders for decision making. This approach helps to visualize, better understand, and make decisions on the aesthetics and the functionality of the space available to the building owner after demolition gets completed in actual.

Lean Construction in Project Demolition Phase

Lean Construction (LC) is referred as the method of production in the construction industry, aimed at reducing costs, and saving material, time, and production effort (Akers, 2016, Warcup, 2015, Karaz et al., 2021). Usage and application of Lean concepts in the deconstruction and demolition phase of projects was found to be rarely mentioned in the literature. However, some insights have been found using the principles that directly conform with those adopted by Lean, for example Pull Planning principles. Schultmann & Rentz (2002) and Marzouk et al. (2019) have somehow referred to the efficiency of using Pull-planning principles in the demolition projects. This principle of Lean promotes pulling the data from downstream instead of the traditional push approach, using the Pull Planning strategy. This can be done by first selecting the building elements to be dismantled and demolished based on the end-customers' needs, and then designing the demolition plan backwards from the that point to reach the desired outcome. Thus, the Pull Planning strategy aids in engaging the customers in the early decision making for prioritizing the demolition plan.

The process of early planning and decision-making in the deconstruction and demolition process is related to making effective real-time decisions early in the process, before the actual demolition begins, on which building elements to be reused, repaired, refurbished, recycled, or sent to the landfills. (Marzouk et al., 2019). Early involvement of stakeholders can serve as a stepping-stone in engaging the demolition contractors and the end-users (customer) willing to purchase the salvaged elements, early in the decision-making of demolition process. Early planning and involvement of potential buyers aid in effective and efficient decision-making process for designing and strategizing the project demolition plan, as per the customer's demand of salvaged and demolished material. From demolition perspective, an important Lean principle related to value generation, which promotes the validation of products against the planned specifications and customer requirements (Sacks et al., 2010). In the context of project demolition, verification, validation, and assurance that all the salvaged elements are dismantled or demolished according to the planned sequence, and that they meet the end-user's requirements, are considered as key parameters or performance indicators that satisfy the customer satisfaction aspect of Lean.

Deconstruction and demolition process can be performed in phases for obtaining the lessons learned from each phase to verify and validate the adopted methodology of Lean based demolition. This principle of Lean promotes the aspect of in-person visual inspections compared to traditional reports (Johnson, Smith, & Mastro, 2012). This concept stresses on the importance of site visits for visual inspection (Sacks et al. 2010). In the context of demolition, visual inspection parameter evaluates both the building's actual current condition and the demolishing elements that have high recovery potential. It is also important for the end-customers who are interested in buying the salvaged elements to visually inspect the quality of demolishing building components before purchasing them. It is worth noting that inspecting the demolition process from the beginning would help in understanding what have been noticed to improve the process and recommending what better can be done for future to improve and restore the quality of demolished and salvaged material for their better re-use in other projects. One of the important principles of Lean is finding simplicity within complex projects (Kalsaas, Skaar, & Thorstensen, 2015) and structuring of the demolition workflow process to separate the standard or similar demolition activities from those demanding the change in information

(Sacks, Derin, & Goldin, 2005). In the context of project deconstruction and demolition, an example of simplicity can be found in trying to detect patterns between the different types of elements that have the same dismantling patterns or methods. Furthermore, another form of process standardization in project demolition is about separating the standard tasks from those subject to information change. This can be achieved by detecting the salvaged elements that are difficult to dismantle and separating their demolition activities from those elements that can be dismantled easily (Marzouk et al., 2019b).\

Development of 3D Demolition Model

An actual ongoing project was used as demolition-based case study for the BIM-Lean based demolition waste management analysis. The 3D model development process begins with the collection of 2D drawings and floor plans of the building from the project owner due to the age of buildings. After the collection of all set of building drawings, a study of structural, architectural, plumbing, and HVAC elements of the building was conducted to understand the building design and analyze the level of design complexity. Further, real-time camera images were taken prior to the start of demolition process for physical analysis of actual condition of the building elements which were to demolish. Later, using the 2D drawings and camera images of building components, 3D model has been constructed using Revit (Figure 1), for reconstructing the demolition model of the building. Due to time limitation, the reconstruction of 3D demolition model was limited to only two rooms of second floor of the building in demolition.

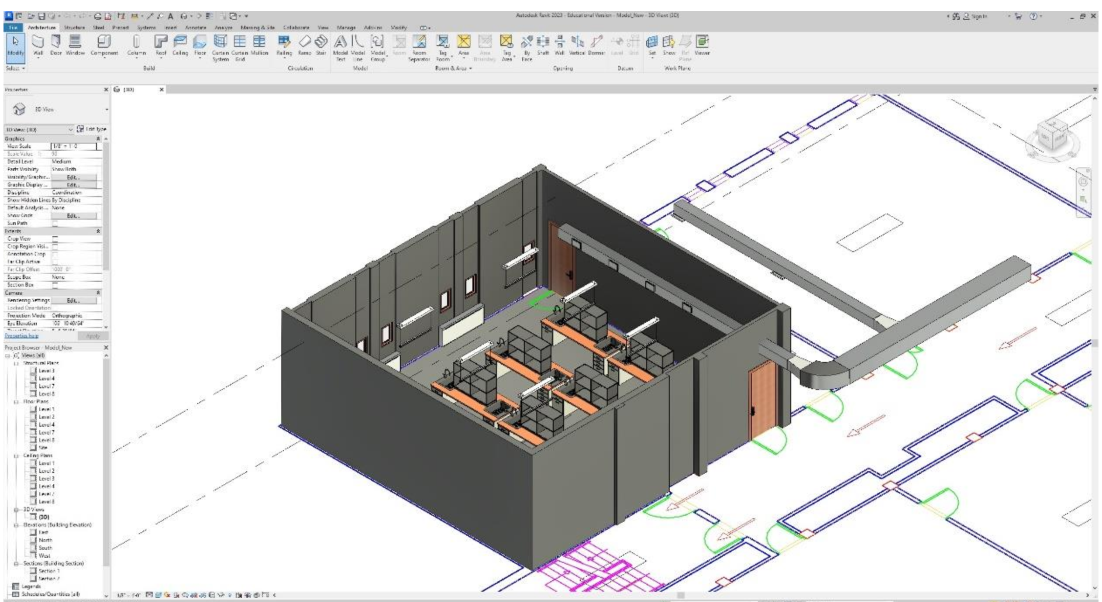

Figure 1. 3D BIM Demolition Model Developed with Revit

After integrating the 2D drawing/floor plans and actual photos of the building elements to be demolished with the reconstructed 3D BIM model, a category-based list of building elements, including furniture, door and windows, light fixtures, plumbing and firefighting accessories, etc. is generated for formulating the Re-use, Recycle, and Disposal destination of the demolished elements in order to optimize the demolition process and deciding final destination of salvaged building material (Table 1).

Using the reconstructed 3D BIM model as mentioned above, material characteristics-based categorization of building elements has been established, by analyzing the current condition and life of building elements (with the help of camera photos available). The purpose of this step is to segregate the building elements based on their characteristics and re-usable capabilities, to classify them into a framework of Re-use, Re-cycle, and Disposal/To-be Landfill categories (see Figure 2). The basic aim of this strategy and designing the material category-based framework is to plan and direct the destination of demolished building elements.

The material or the building elements with least re-usable condition and below acceptable standard life will be sent directly to disposal without any further process on them. Material possessing re-usable or re-cyclable characteristics (by visualizing the photos) will be considered for their reuse into other similar projects, based on the input and requirements from building owner or stakeholders (client) using the information obtained from constructed 3D BIM demolition model (Table 1).

Table 1. Demolished material categorization of building elements using 3D model visualization

Demolishing Material Category	**Reuse**	**Re-cycle**	**Disposal/To-be-Landfill**
Civil/Architectural Elements			
Furniture (wooden shelves)			
Furniture (tables)			
Flooring (tiles)			
Concrete (column)			
Concrete (wall & floor)			
Ceiling			
General Doors			
Fire Doors			
Window Glass			
Window Frames			
MEP Elements			
Ceiling Lights			
Table Sinks			
Electric Unit Ventilator			
HVAC Elements			
Grills and Diffusers			
Square Duct			
Duct Connector			
Duct Connector (90º)			

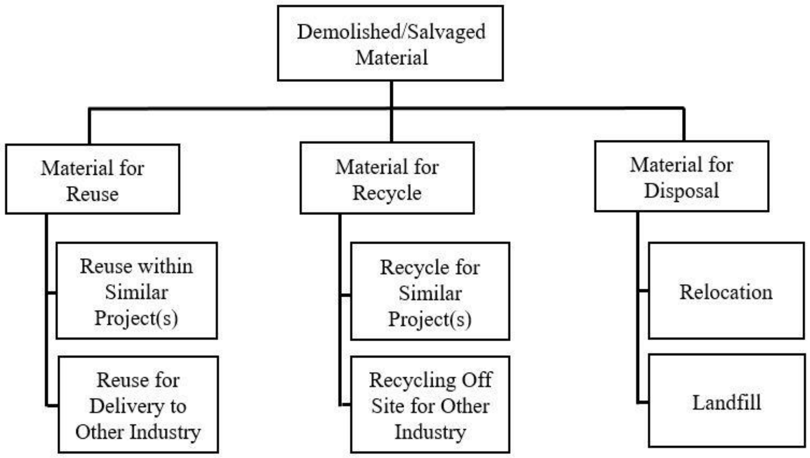

Figure 2. 3D BIM model-based demolition material categorization framework

Discussion

The utilization of created 3D BIM demolition model encourages the involvement and participation of the project owner, i.e., client, in planning and directing the demolition process. Based on the reconstructed 3D BIM demolition model and the building images available of the items to be demolished, inputs from the building owner/project client can be taken at this point for prioritizing the demolition activities based on clients' demands of building elements to be demolished. Development and use of as-built 3D BIM demolition model (using Revit and Navisworks software) can aid and simulate in linking the demolition flow process with the supply of salvaged elements, aligning with the customer's needs. Model simulated on Navisworks, linked with the real time images of building elements, can provide good visualization for clients to make early decisions on whether to Re-use, Re-cycle, or Disposed the material. Figure 3 below depicts how this synchronized decision-making process can work for optimizing the best use of demolished material.

At this stage, one of the core principles of Lean, i.e., Customer Satisfaction, gets involved in the deconstruction and demolition process. As the customer can be mainly the potential buyer of these dismantled salvage material, so the quality of salvaged building elements to be dismantled can be visualized and analyzed even prior to the start of the actual demolition process. The customer can be from recycling facilities background that deal with the new construction projects that directly reuse the salvaged elements into their other new projects, resulting a considerable amount of monetary saving for procuring new construction material.

Based on the proposed client's requirement-based demolition model and waste management framework, material's Re-use, Re-cycle and Disposal destinations can be planned prior to start of actual demolition. Use of BIM model provides visualization of building elements that are to demolish, to the stakeholders (client) in pre-demolition stage. This approach can be expected to potentially enhance the decision-making process for the salvaged and demolished material for planning their destination in advance before actual demolition process starts. This study is expected to promote a behavior change in the construction industry towards improving the circular economy by encouraging salvaged material Re-use and Recycle strategies and lowering the disposal of demolished material to the Landfill sites. Further, for future work, BIM based project demolition cost information can help the project team to forecast and estimate complete demolition cost. It can aid in decision-making process for the project owner and other stakeholders for initiating the demolition process based of material's cost-effective reusability factors. Identification of demolishing material in pre-demolition phase can potentially assist in formulating waste management strategies as per the need of the customer/buyer of salvaged material.

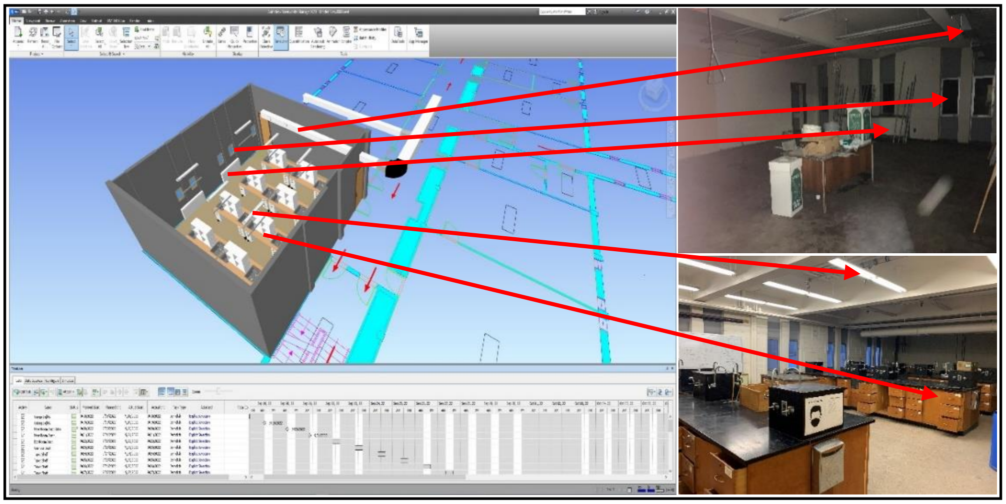

Figure 3. 3D BIM Model-based Simulation of Demolition Process

Conclusion

This paper has explored the usability of reconstructed 3D demolition model to analyze the integrated approach of BIM and Lean Construction for developing client's requirement-based demolition model and waste management framework. Based on the study on BIM-Lean synergy at project demolition stage, and analysis of the reconstructed 3D demolition model, the conclusions that can be drawn are:

- the use of reconstructed 3D demolition model provides visual environment for the client, in pre-demolition stage, which can potentially enhance the decision-making process for the salvaged material;
- the use of BIM model provides visualization of building elements that are to demolish, and thus making demolition waste management plans more efficient due to planning of the final destination of salvaged and demolished material prior to the start of actual demolition; and
- the identification of demolishing material in pre-demolition phase assists in formulating waste management strategies as per the need of the client.

A combination of the conclusive findings indicates that the approached presented in this paper can help improve the rate of reuse and recycle of demolished material, that can ultimately lead to sending less material to landfill/disposal sites. Further, logistical costs of mobilizing unnecessary (unwanted) demolished material to the landfill sites can also be efficiently reduced to a greater extent. Deciding demolished material's destination prior to start of actual demolition can aid to resolve mismanagement of bulk demolished building material handling and storage at project site. Overall, more resources can be preserved.

Acknowledgment

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References

Akers, P. A. (2016). 2 Second Lean-: How to Grow People and Build a Fun Lean Culture. BookBaby.

Akinade, O. O., Oyedele, L. O., Omoteso, K., Ajayi, S. O., Bilal, M., Owolabi, H. A., … Henry Looney, J. (2017). BIM-based deconstruction tool: Towards essential functionalities. International Journal of Sustainable Built Environment, 6(1), 260–271. https://doi.org/https://doi.org/10.1016/j.ijsbe.2017.01.002

Eastman, C. M., Eastman, C., Teicholz, P., Sacks, R., & Liston, K. (2011). BIM handbook: A guide to building information modeling for owners, managers, designers, engineers and contractors. John Wiley & Sons.

Johnson, J. E., Smith, A. L., & Mastro, K. A. (2012). From Toyota to the bedside: nurses can lead the lean way in health care reform. Nursing Administration Quarterly, 36(3), 234–242.

Kalsaas, B. T., Skaar, J., & Thorstensen, R. T. (2015). Pull vs. push in construction work informed by Last Planner. Proc., 23rd Annual Conference of the International Group for Lean Construction, 103–112.

Karaz, M., Teixeira, J. C., & Rahla, K. M. (2021). Construction and demolition waste—A shift toward lean construction and building information model. In Sustainability and Automation in Smart Constructions (pp. 51–58). Springer.

Lean Construction Blog. (n.d.). Lean and BIM Synergy in Practice – A General Overview. Retrieved October 26, 2022, from https://leanconstructionblog.com/Lean-and-BIM-Synergy-in-Practice%E2%80%93A-General-Overview.html

Li, C. Z., Zhao, Y., Xiao, B., Yu, B., Tam, V. W. Y., Chen, Z., & Ya, Y. (2020). Research trend of the application of information technologies in construction and demolition waste management. Journal of Cleaner Production, 263, 121458.

Marzouk, M., Elmaraghy, A., & Voordijk, H. (2019a). Lean deconstruction approach for buildings demolition processes using BIM. Lean Construction Journal, 147–173.

Marzouk, M., Elmaraghy, A., & Voordijk, H. (2019b). Lean deconstruction approach for buildings demolition processes using BIM. Lean Construction Journal, 147–173.

NBIMS, N. B. (2010). National BIM Standard-United State. Building Smart Alliance.

Nikmehr, B., Hosseini, M. R., Wang, J., Chileshe, N., & Rameezdeen, R. (2021a). BIM-Based Tools for Managing Construction and Demolition Waste (CDW): A Scoping Review. Sustainability, 13(15), 8427.

Nikmehr, B., Hosseini, M. R., Wang, J., Chileshe, N., & Rameezdeen, R. (2021b). BIM-Based Tools for Managing Construction and Demolition Waste (CDW): A Scoping Review. Sustainability, 13(15), 8427.

Sacks, R., Derin, Z., & Goldin, M. (2005). Pull-driven construction of high-rise apartment buildings. 13th International Group for Lean Construction Conference: Proceedings: Proceedings, 217–226. International Group on Lean Construction Sydney.

Sacks, R., Koskela, L., Dave, B. A., & Owen, R. (2010a). Interaction of lean and building information modeling in construction. Journal of Construction Engineering and Management, 136(9), 968–980.

Sacks, R., Koskela, L., Dave, B. A., & Owen, R. (2010b). Interaction of lean and building information modeling in construction. Journal of Construction Engineering and Management, 136(9), 968–980.

Schultmann, F., & Rentz, O. (2002). Scheduling of deconstruction projects under resource constraints. Construction Management & Economics, 20(5), 391–401.

Shen, L. Y., Tam, V. W. Y., Tam, C. M., & Drew, D. (2004). Mapping approach for examining waste management on construction sites. Journal of Construction Engineering and Management, 130(4), 472–481.

Warcup, R. (2015). Successful paths to becoming a lean organization in the construction industry. Utah State University.

Yuan, H., & Shen, L. (2011). Trend of the research on construction and demolition waste management. Waste Management, 31(4), 670–679.

The Impact of Mechanical & Plumbing Change Orders on USACE Construction Projects

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This research studied contract change orders at five U.S. Army Corp of Engineers (USACE) Districts over the past twenty-one years with a combined value of $3,689,742,841. These districts represent a broad spectrum of federal contracting across the entire United States and every type of construction contract from major military projects to minor repair work to national civil infrastructure. Of the 44,887 contract changes studied, 4,061 were identified as specifically related to the Mechanical and Plumbing trades. These changes were evaluated for magnitude, frequency and time extension. The Mechanical and Plumbing trades were selected because they are typically among the last major construction features prior to the completion date. Previous research estimates that change orders in the last 20% of a project timeline should be weighted 6 times more heavily than change orders in the first 20% (Hanna et al., 1999). The results indicate that Mechanical and Plumbing change orders do have a higher likelihood of extending the timeline of a project. It also showed that the dollar value impact was relatively low compared to other changes. Ultimately the database of contract changes generated during this research could provide a critical data source for future studies, particularly of federal construction contracting.

Key Words: Change Order, Modification, Mechanical, Plumbing, Federal Contracting

Introduction

In the high-stakes world of construction management everyone hates change orders. These contract changes become even more odious when they occur near the end of a project. Usually at this point the entire project budget is obligated and the occupancy date is imminent. Two of the trades with the largest potential for impact at the end of a project are the Mechanical and Plumbing trades. This research seeks to analyze the magnitude, frequency, and time impact of these types of change orders.

By determining the actual trends in Mechanical and Plumbing change orders we can better understand their impact and develop mitigation strategies. The purpose is to understand the actual statistical frequency of Mechanical and Plumbing change orders on USACE construction contracts to see if there are any strong correlations or tendencies. This work will provide the groundwork necessary to study specific situations and potential solutions for late-stage construction changes.

Measuring the cost and time extension of a very large number of Mechanical and Plumbing contract changes will identify possible correlations that should be further studied to improve end-of-project efficiency. Ultimately, this research could reduce late changes to construction contracts and therefore significantly reduce frustration associated with contract closeout. Previous research shows that design changes and schedule delay (delays caused by others) are the two greatest contributors to project delays (Asmi et al., 2019). This work will seek to identify the underlying factors and see which types of changes are causing the delay.

Data and Terminology

The data for this research comes entirely from U.S. Army Corps of Engineers (USACE) projects. These projects represent nearly all change orders from the 21-year period of 2002 to 2022. Research was limited to five USACE districts: Baltimore, Ft. Worth, Louisville, Seattle and Wilmington. These districts each have significant Military Construction (buildings) and Civil Works (infrastructure) projects and represent a cross-section of the entire continental United States. The result is a comprehensive review of over 44,000 construction change orders. This research will use the common term "change order" throughout. In federal contracting, change orders are more frequently known as "contract modifications" or as "change requests".

Defining a Change Order

It is important to understand what is considered a change order and how it may differ across the construction industry. Broadly speaking, a change order is any change to a construction contract after the original award of the contract to a contractor or subcontractor. However, this general definition quickly runs into nuances and caveats. A more specific definition would be any material change to a construction contract that causes a change in cost, time or final product.

The federal contracting used in this research has two fundamental types of change orders that can generally be categorized by the approval authority: either Contracting Officer or Administrative Contracting Officer. Contracting Officers typically sign the original agreement between the United States Government and a Prime Contractor. This agreement for construction services (a built product) in exchange for money is called the contract. Contracting Officers also sign contract modifications that are primarily administrative in nature. These include: Notice-to-Proceed, award of contract options, funding updates and any clerical changes. Finally, if a change order during construction exceeds the authority of the Administrative Contracting Officer, then the Contracting Officer can sign. This research seeks to eliminate the administrative types of change orders from consideration, while still retaining any true material changes that may be signed by a Contracting Officer.

Administrative Contracting Officers (ACO) can sign change orders up to an absolute value of $500,000. These change orders are almost always true material changes to the contract. The ACO is the primary signature authority for construction changes that happen after Notice-to-Proceed. The ACO is typically a supervisor with direct involvement on the specific project. Although it is possible for a change order to be approved quickly, the nature of federal contracting tends to result in an extended approval period. This is critically important because construction is very dependent on scheduling and sequencing. An unapproved or delayed change order can significantly impact project duration and cost. This issue has even been brought before the U.S. Congress because of how badly it can affect small contractors even to the point of bankruptcy. (*All Work and No Pay*, 2017)

This research will only address the change orders between USACE and a prime contractor that are signed by the Contracting Officer or the Administrative Contracting Officer. It will not address the numerous changes between prime contractors and subcontractors. It will also not address any unwritten changes or “trades” that can happen during contract performance.

Literature Review

Michael T. Callahan developed an excellent resource for change orders titled “Construction Change Order Claims” (Callahan, 2005). One of his key points is that changes must be “identified and corrected early, when changes cost little or nothing, before the project moves into the high-spending procurement and construction phases”. Given the high priority on identifying changes early, this research on mechanical and plumbing changes seeks to identify the types of changes that typically happen late in a project so that they can be avoided.

In James O’Brien’s book “Construction Change Orders: Impact, Avoidance, Documentation”, he states “Experienced contractors know that there will be unforeseen conditions and unexpected situations for which time extensions will be allowed. The contractor also expects changes on the part of owners and anticipate that either the owners will relax end dates, or, if need be, they will successfully handle any delay claims by the owners.” (O’Brien, 1998). Since this book is primarily written to the construction contractor, it makes sense that the owner representatives need to know and understand the same dynamics at play within the construction contract. This research should provide the background information to both parties in order to help make informed decisions.

Jieh-Haur Chen and S.C. Hsu developed an Early Warning System (EWS) has been developed to identify change orders with the greatest likelihood of resulting in court claims. Their recommendation is that relatively small projects have a higher probability of costly claims. These small projects tend to get less attention, have less detailed plans and the bidding process is less thorough. They state that “owners and contractors should pay more attention if their projects are relatively smaller (<1 million dollars)”. (Chen & Hsu, 2012)

During this review of available information, it was determined that much of the data relies on surveys or a relatively small sample size of change orders. One example of this is a study done for the Illinois Department of Transportation (IDOT). The introduction states that the value of construction change orders in the United States is between $76 billion and $152 billion. However, the study goes on to review just 50 change orders as it seeks to identify root causes that will aid in the management of change orders. (Assaad et al., 2022) Ultimately the IDOT study identified the number one cause of change orders as "Contract Administration" at 28% and found that only 8% were due to design changes and 10% to differing site conditions.

One thing that stands out is the importance of timing in construction changes. Evidence that late changes are particularly troublesome includes an article titled "The impact of change orders on mechanical construction labour efficiency". The authors used a quantitative model to prove that projects with schedule impacts cause a significant decrease in labor efficiency and showed that the later the change occurred in the schedule the greater the decrease in efficiency (Hanna et al., 1999). This means that mechanical and plumbing contractors have the most to lose when projects get delayed. Even when they successfully bid the changed work, the fact that the labor is less efficient means that the project will actually cost the contractor more than they planned. This study used 90 changes across 57 projects.

One resource even goes so far as questioning whether construction contractors can predict and take advantage of potential change orders. A study done at Purdue University and Ball State University reviewed 30 California Department of Transportation (Caltrans) projects that had unit-priced line items. They proved that "more than 70% of the items with final quantity more than estimated ones were priced higher than average by the contractor." (Shafaat et al., 2016). This research should be sobering to public and government contracting agencies because they are the ones most likely to write their own contracts. It appears that contractors can accurately identify risk for changes and will increase price accordingly to maximize profit on changed work.

Additional research on labor efficiency has developed a model for predicting impact for the mechanical trades. (Hanna et al., 2002) One of the key elements in this model is a factor called "Percent Design Changes". This factor uses a ratio of change order types: mechanical vs. all change orders. The larger the ratio of mechanical changes to total changes, the larger the potential impact. The bottom line is that with all other factors held constant, the ratio of change orders determines the probability that impact is happening on a project by approximately 23%. This model could be used in conjunction with this research to more accurately identify and resolve potential impacts before they occur. If we can identify the particular types of changes that are happening in the mechanical and plumbing trades, then we can lower the ratio and reduce the probability of impact. This in turn will improve labor efficiency.

One additional piece of research identified that the timing of changes matters (beginning, middle or end), but did not use that information in the remainder of their research (Waty & Sulistio, 2022). This research was also based on survey respondents. It did reach a consensus with other research in identifying some of the most common causes. Mismatches between design drawings and field conditions came in first on the list of causes and third on the list of group categories.

Research Methodology

The design for this research was to gather a very large volume of historical construction change order data and perform trend analysis. The analysis consisted of two basic phases. Phase One sorted and processed 100% of all construction change orders. This phase included a preliminary trend analysis to determine the ratio of Mechanical and Plumbing changes to the total of all changes. Phase Two looked closer at the Mechanical and Plumbing changes only to determine any specific trends related to contract impact that vary from baseline of all changes.

This research is focused on a specific set of construction change orders for which data is available in the USACE *Resident Management System*. This system is known as RMS 3.0 and has been in use by USACE since the late 1990's. However, it really became widespread and fully implemented for construction contract change orders around 2002. This software program is a database of construction contracts between the federal government (USACE) and many prime contractors that meet the standards required to bid on federal work. All Contracting Officer change orders involving time or money and all ACO change orders are required to be recorded in the RMS system. One change order in the RMS system may represent multiple discreet contract changes, but typically they are one-to-one.

The database is organized by USACE district and by specific contract number. This number is typically a 13-digit number consisting of a six-digit district identifier, a two-digit fiscal year, a letter, and a four-digit number. Modifications to contracts are identified by up to six digits but are typically in the form “P00001” for Contracting Officer changes and “A00001” for ACO changes.

Phase One data gathering consists of running a summary report at the USACE District level for all “completed” change orders. The title of the report is “Construction Contract Modifications”. This report is generated in Microsoft Excel. Since the report uses database-specific language and formatting, the result is a text field of all the relevant modification data. It is then necessary to process the data using several Excel formulas to create a sortable list of numerical values. In Phase One, it is not necessary to know the specific contract or even the specific timing within the contract. The key data points during this phase are the value in dollars and the time in days. This data will then be further refined by identifying which change orders are specifically related to Mechanical and Plumbing trades. Finally, the data will be scrubbed to remove any purely administrative changes. In this final step, only two types of changes will be removed: Contract Options since they should be considered part of the original contract, and administrative changes with a $0 value and 0 days in time.

Phase Two data gathering consists of identifying and reviewing the Mechanical and Plumbing changes only and comparing the magnitude, frequency, and time extension to the larger body of all change orders. In this phase we are seeking to identify any statistically significant trend that shows a variation in these change orders. The large volume of data should provide a clear and measurable outcome if the Mechanical and Plumbing changes are truly different. This phase will use a variety of charting strategies to see whether any variations can be observed.

As mentioned in the introduction, none of the data being collected represents change orders between the prime contractor and the subcontractors. The bottom line is that change orders between the owner and the prime contractor are more significant than those with subcontractors because they represent an actual change to the firm-fixed-price agreement. A prime contractor is generally not permitted to pass cost increases or delays to the owner if there is no change to the contract. However, between prime contractors and subcontractors many things are negotiable and could be subject to these types of change orders even if the original contract with the owner is unchanged.

Data Collection and Analysis

Data collection started with RMS database reports for change orders on 11 May 2022. These reports included all the change orders from 2002 to the report date in 2022. This data collection assumes that all contract changes during this period were correctly recorded in the RMS system. This assumption is highly likely because this system is also used to make payments on USACE construction contracts, which cannot happen if the underlying financial data does not match across all systems.

The data initially formed five distinct MS Excel reports, one for each district. Due to the text-style formatting, multiple administrative formulas needed to be used to refine the data to true numbers-based spreadsheets. The title of each modification was retained so that it could be located later for the purposes of future research. The initial set of data returned a total of 44,887 construction contract change orders. This includes contract options, administrative changes, $0 changes as well as every true construction change. Table 1 shows theses totals organized by the dollar value magnitude of the change. This phase of the research is sorted by arbitrary dollar magnitude categories to try to show the frequency of each type of change order Figure 1 demonstrates this.

This initial dataset had some fascinating statistics. Here is a brief overview of some of the highlights. The total absolute value of these change orders was $3,689,742,841.14. The total contract increase came in at just under $3.5 billion. The average cost per change order was $82,200.70.

The impact on the contract duration was also significant. This data represents a total increase of 571,521 days to these federal contracts. Of all the change orders 9,496 had time extensions representing 21% of all changes. The average time extension on changes that included time was 60 days. This two-month extension marks a significant impact on the overall completion schedule. Prior to the start of the project, government management teams typically allow a move-in schedule approximately 90 days after contract completion. This means that the average individual time extension modification is using up two thirds of that buffer.

Table 1

Initial Data Set of Contract Change Orders

Magnitude	Baltimore	Ft. Worth	Louisville	Seattle	Wilmington	Total
$1M+	50	218	209	21	98	596
$500k - $1M	53	187	219	19	65	543
$100k - $500k	517	1,281	1,672	232	352	4,054
$50,000 - $100k	480	1,123	1,656	234	228	3,721
$25,000 - $50,000	551	1,357	2,161	222	245	4,536
$10,000 - $25,000	801	1,815	3,426	268	349	6,659
$5,000 - $10,000	571	1,209	2,358	135	186	4,459
$1 - $5,000	780	1,785	3,742	117	207	6,631
Equal to $0	454	4,056	3,671	202	767	9,150
$0 to ($50,000)	322	1,008	1,691	130	190	3,341
($50,000) to ($500k)	111	432	363	70	139	1,115
($500k)+	7	30	13	5	27	82
Total	4,697	14,501	21,181	1,655	2,853	44,887

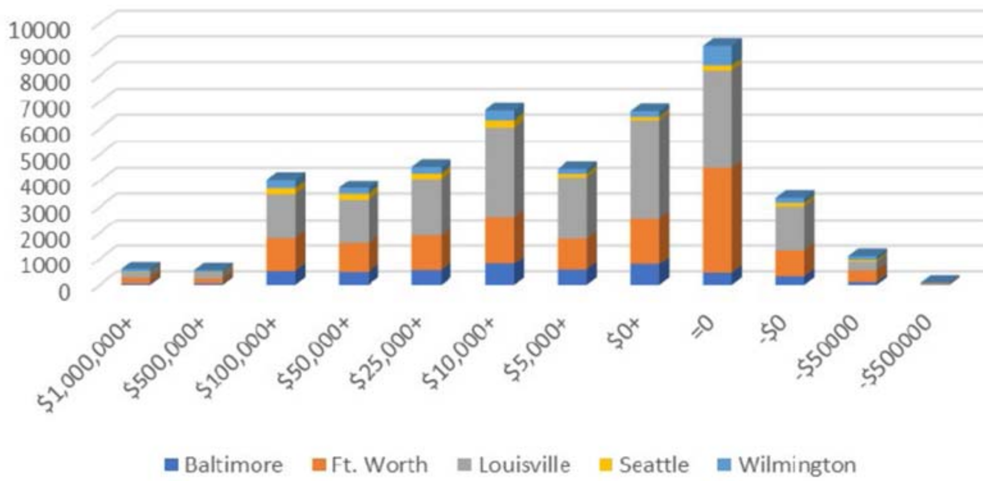

Figure 1. Change Order Frequency and Magnitude

After compiling the initial dataset, the data was reviewed to isolate the change orders that were specifically related to Mechanical and Plumbing. The first step in this process was to eliminate as many of the administrative change orders as possible. Almost all Contract Options were eliminated. These are priced with the original contract bid proposal and should be considered part of the original contract award. Additionally, almost all change orders with a $0 value and 0-day time extension were removed. However, some change orders in this category were retained if they were specifically related to Mechanical or Plumbing work. The goal with this was to eliminate as many purely administrative changes as possible.

The second step involved manually searching through the data for change orders that were most likely specifically related to Mechanical and Plumbing. This review and searching process required judgement and construction contracting experience. For example, a change titled "AHU piping" would make the list, but one titled "AHU structural support" would not. The difference being that second example involves the building structural trades and would typically not involve the mechanical subcontractor. The primary method of this research was key-word searches throughout the entire data set. Table 2 provides a list of all key words and abbreviations that were used to refine the data.

Table 2

Key Words Used to Refine the Data

Mech*	Plumb*	Exhaust	Fan	Vent	Heat	Cool
Valve	Water	Duct	Gas	Condensate	Sprinkler	Fire
Louver	Chiller	Pip*	AHU	ACCU	VAV	BCU
FCU	MAU	BMS	DDC	MEP	HVAC	

The refined set of data returned a total of 4,061 construction contract change orders specifically related to the Mechanical and Plumbing trades. This means that for federal contracting 9% of all contract changes are specifically Mechanical or Plumbing related. The data by district is summarized in Table 3 and Figure 2.

Table 3

Refined Data Set of Contract Change Orders

Magnitude	**Baltimore**	**Ft. Worth**	**Louisville**	**Seattle**	**Wilmington**	**Total**
$1M+	3	14	2	0	1	20
$500k - $1M	1	7	7	3	2	20
$100k - $500k	61	88	121	46	16	332
$50,000 - $100k	64	116	130	39	5	354
$25,000 - $50,000	96	156	225	48	11	536
$10,000 - $25,000	183	222	356	60	18	839
$5,000 - $10,000	96	159	251	27	22	555
$1 - $5,000	119	226	440	28	11	824
Equal to $0	23	182	64	7	3	279
$0 to ($50,000)	30	80	109	14	6	239
($50,000) to ($500k)	16	28	14	1	0	59
($500k)+	0	2	1	1	0	4
Total	692	1,280	1720	274	95	4,061

At this point, we noticed that the most frequent change order type in the full set was equal to $0. These administrative changes dominate the first graph, but in the M&P graph they are one of the smaller totals. We also see that the M&P change orders with by far the greatest frequency are also very small changes. The first is the set ranging from $1 to $5,000 and the second is the set ranging from $10,000 to $25,000. This is an early indication that the M&P change orders might consist largely of very small changes.

The M&P-specific dataset also provided statistics that were important because they showed clear differences from the larger group of change orders. The total absolute value of these change orders was $194,362,596.86. The total contract increase came in at just over $181 million. This represents a small fraction of the $3.5 billion. The average cost per change order was $47,860.77.

The impact on the contract duration was also significant. This data represents a total increase of 41,447 days. Of all the M&P change orders 15% had time extensions included for a total of 610 discrete changes. The average time extension on changes that included time was 68 days.

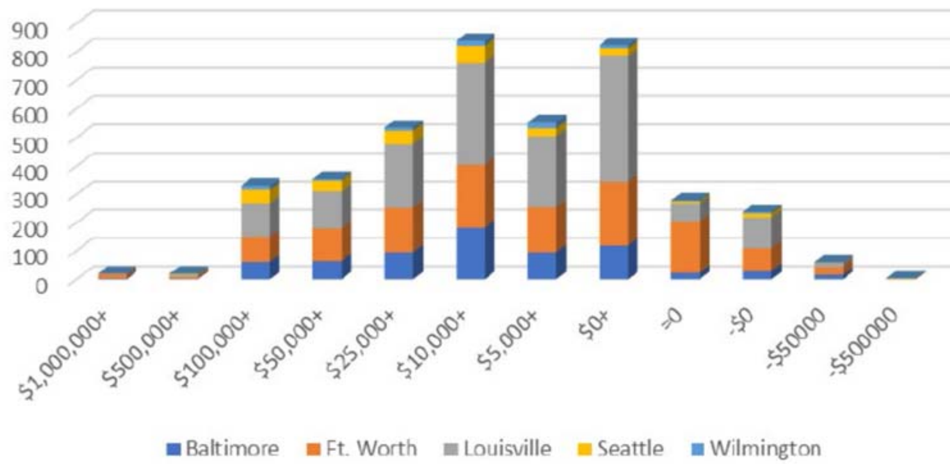

Figure 2. Mechanical & Plumbing Change Order Frequency and Magnitude.

The first comparison review of all the data was not as satisfactory as expected. Especially when analyzing the cost information, it became clear that the M&P data closely mirrored the rest of the data. When plotting all change orders, there is a much higher frequency of "small" change orders and much greater impact from a few "large" change orders. As a result, the research was modified slightly to create change order groupings that best represented equal dollar value magnitudes. The basic approach was to take the total increase amount of $3.5 billion and divide it into 15 equal groups of approximately $228 million each. The "equal value" method stays close to the $228 million target in almost all categories except the range from positive $5,000 to negative $35,000. The absolute value of all the changes in this range is only 20% as much as the target value simply due to the very small values being tracked. Using this method resulted in the categories and results shown in Table 4.

A very important statistical result came from this method of data organization. For M&P change orders, almost half (49%) are found in the 4 groupings from $5,000 to $225,000. In comparison to the full list which has only 26% of the total in these same groupings. In the full list, the top four categories equal 0.5% of all the changes but represent 25% of the total value. To get to the same 25% value mark for the M&P changes you would need the top eight categories and 1% of all the changes.

Table 4

Change order groupings that best represented equal dollar value magnitudes

Magnitude	Full Count	M&P Count
$7M - $10M	27	0
$5M - $7M	37	0
$3.5M - $5M	55	0
$2.5M - $3.5M	91	5
$1.75M - $2.5M	118	2
1.2M – 1.75M	159	6
$800k - $1.2M	276	10
$500k - $800k	399	20
$350k - $500k	629	45
$225k - $350k	966	61
$125k - $225k	1,695	139
$75,000 - $125k	2,331	221
$35,000 - $75,000	4,454	470
$5,000 - $35,000	13,438	1,691

$1 - $5,000	6,524	810
Equal to $0	9,150	279
$0 to ($35,000)	3,061	221
($35,000) to ($1M)	1,477	81

In a final round of data analysis, the worst M&P change orders were analyzed by type. This stage looked at only change orders with a dollar value greater than $500,000 (exceeding the ACO authority) or a time extension greater than 180 days (significant impact to the move-in date). Over the 21-year period being reviewed, there were 101 change orders that fit this description as the worst M&P changes. They could be easily categorized into the following sets: Control Systems (DDC), Design, Gas, HVAC, 1:1 Replacement, Sewer, Sprinkler, Temporary Facilities and Water. Of these sets, the Design, 1:1 Replacement and Temporary Facilities are all changes that are likely to have happened early in the construction project. These totaled 14 of the 101 changes and most did not have a time extension. The worst M&P changes with the highest frequency were HVAC changes at 52, Water system changes at 15 and Sprinkler changes at 10.

Conclusions and Recommendations

This research shows that Mechanical and Plumbing change orders are typically a less significant problem than originally anticipated. The time extension associated with certain M&P change orders does show a measurable increase. However, the dollar value associated with these changes is surprisingly low. Mechanical and Plumbing change orders have an average price of $47,860.77 compared to $82,200.70 for all change orders. This is a statistically relevant comparison with a 42% lower dollar value. However, they have an average time extension of 68 days compared to 60 days. This 8-day increase per change order is also significant. It shows that when an M&P change order impacts a project, it is likely to have a greater time extension than other types of impacts.

Since M&P change orders are relatively small and since they have a larger time impact, it is imperative that both the government and the contractor's on-site contract management teams are prepared to quickly execute any late-stage M&P changes. The more quickly the owner and prime contractor can reach an agreement on these relatively small changes the greater the chance of a successful project outcome and on-time move-in. It is strongly recommended that any owner, and in particular the U.S. government, develop a rapid approval process at the lowest on-site management level. This would typically be an on-site Quality Assurance Representative or Contracting Officer's Representative (COR). Even an on-the-spot approval authority as small as $35,000 would account for 15% of all M&P changes. If this had been applied to this historical data, it would have only cost the government a little over $1,000,000 per year. Additionally, if it is applied in the future, that number will likely grow to several million dollars per year as more changes are made quickly at the lowest level and don't grow into larger and more expensive problems. Contractors would also gain in confidence that these little annoying late-stage changes could be resolved satisfactorily without significant administrative burden.

This analysis also shows that in most cases the M&P problems are relatively simple to correct. During the key-word search, it quickly became apparent that many of the changes were things that could be resolved in a few days. Some very common results had titles like:

- *"Adjust HVAC Ductwork"*
- *"Replace Chiller Pump"*
- *"Differing Site Condition – Water Main Location"*
- *"Relocate Sprinkler Line"*
- *"Add Cooling to Room ###"*

The recommendation for all field-level on-site construction management teams is to be prepared for these common M&P changes. Prior to every project, contractors should assume that the existing water main will not be in exactly the right location and that the HVAC design will miss or inaccurately represent at least one room and that the sprinklers will have to be adjusted to match actual conditions. If these problems represent a change to the contract, then be prepared to quickly price them and provide sufficient supporting data to allow quick financial approval by the government official.

References

All work and no pay: Change orders delayed for small construction contractors : hearing before the Subcommittees on Contracting and Workforce and Investigations, Oversight, and Regulations of the Committee on Small Business, United States House of Representatives, One Hundred Fifteenth Congress, first session, hearing held May 25, 2017 (AU Electronic Resource Y 4.SM 1:115-022). (2017). U.S. Government Publishing Office.

Asmi, A., Djamaris, A., & Ihsan, M. (2019). Top Ten Similarity Ranking for Project Delay Factors in Construction Industry. IOP Conference Series: Materials Science and Engineering, 650(1), 012006. https://doi.org/10.1088/1757-899X/650/1/012006

Assaad, R. H., Ahmed, M. O., El-adaway, I. H., & Shrestha, P. P. (2022). Management of Change Orders in Infrastructure Transportation Projects. Practice Periodical on Structural Design and Construction, 27(1), 05021006. https://doi.org/10.1061/(ASCE)SC.1943-5576.0000640

Callahan, M. T. (2005). Construction Change Order Claims. Wolters Kluwer.

Chen, J.-H., & Hsu, S. C. (2012). Early Warning System for Severe Change Orders. 1–12. https://doi.org/10.1061/40794(179)178

Gould, F. E., & Joyce, N. (2003). Construction project management (LADC Auburn TH 438 .G62497 2003; 2nd ed.). Prentice Hall.

Hanna, A. S., Camlic, R., Peterson, P. A., & Nordheim, E. V. (2002). Quantitative Definition of Projects Impacted by Change Orders. Journal of Construction Engineering and Management, 128(1), 57–64. https://doi.org/10.1061/(ASCE)0733-9364(2002)128:1(57)

Hanna, A. S., Russell, J. S., & Vandenberg, P. J. (1999). The impact of change orders on mechanical construction labour efficiency. Construction Management and Economics, 17(6), 721–730. https://doi.org/10.1080/014461999371060

O'Brien, J. J. (1998). Construction change orders: Impact, avoidance, documentation. (LADC Auburn TH 438 .O27 1998). McGraw Hill; Auburn University Library Catalog. http://spot.lib.auburn.edu/login?url=https://search.ebscohost.com/login.aspx?direct=true&db=cat07161a&AN=aul.2418787&site=eds-live&scope=site

Resident Management System, RMS 3.0, https://rms.usace.army.mil, U.S. Army Corps of Engineers

Shafaat, A., Alinizzi, M., Mahfouz, T., & Kandil, A. (2016). Can Contractors Predict Change Orders? Investigating a Historical Allegation. 487–496. https://doi.org/10.1061/9780784479827.050

Waty, M., & Sulistio, H. (2022). Causes for the Change Orders in Road Construction: Reviewed from Owner. Communications - Scientific Letters of the University of Zilina, 24(2), D72–D84. https://doi.org/10.26552/com.C.2022.2.D72-D84

BIM Data Handover from Construction to Operations

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Facility owners and managers rely on trusted asset data developed during projects in BIM for reducing risk in operations, strategic planning, design, construction, sustainability, and environmental responsiveness. The prime contractor is the party responsible for construction handover and for fulfilling the project owner's requirements to deliver the building information model (BIM) and the asset data as set forth in the BIM Project Execution Plan (BEP). This research was approached with a broad perspective of the state-of-practice of BIM data use for Facilities Management (FM). Using a questionnaire sent to facility owners, managers and those in similar positions this study sought to identify why the project data handover from construction is vital to facilities management for operations and maintenance, and how the project data is collected and used for facilities management purposes. The results discussed here were limited to Construction Deliverables and Facilities Management. The research found that following a prescribed process for understanding O&M needs, as defined in the UK for some years, could help. Understanding the issues identified in this paper is a great starting point for construction handover. Reflections from this study should be applicable for O&M stages in both the USA and UK respectively.

Key Words: BIM, Construction Handover, Operations & Maintenance, Facilities Management

Introduction

The handover stage of a project from construction to operations is crucial for facility owners as it is the stage where they are provided the relevant building data needed to operate the facility (Cavka, Staub-French, and Poirier, 2017). Information provided at this point will be used for the operations and maintenance stage (O&M) over the remaining lifecycle of the building. The prime contractor is the party responsible for construction handover and for fulfilling the project owner's requirements to deliver the building information model (BIM) and the asset data as set forth in the BIM Project Execution Plan (BEP). The level of information required at construction handover varies by project owner. For example, the Massachusetts Port Authority (MPA) BIM Guidelines requires handover of data at the end of construction that includes the as-built model and construction to operations building information exchange (COBie) worksheets with special emphasis on spaces, MEP, and equipment for facilities handover. Additionally, the as-built model is required to provide an archival record of what was constructed at a higher level of development (LOD) than the record model. The guidelines allow for the as-built model to also contain additional file formats from shop models and fabrication detailing with information coordinated in the project, where exactly the new or renovated work is located (Massport, 2015). In the United Kingdom, Gatwick Airport's BIM processes and principles were created in 2012 to support handover from construction to O&M (Bechtel, 2014; Hulse, Cod, and Neath, 2014). At Gatwick Airport the owner's information requirements (OIR) are developed by the airport and used to create the asset information requirements (AIR). In the AIR, all the asset types corresponding to what information should be recorded are identified and listed by the function the asset would perform. For each asset, multiple property sets are defined in the AIR, included in the model during design and construction phase and handed off to asset management at the end of the project (Mallela, Blackburn, Grant, Kennerly, Petros, and Yew, 2020). Like Massport, the Gatwick BIM requirements ensure that the required asset data is included in the model for seamless handover of project data models to asset managers for their development and maintenance of the asset information model. These are just two examples of project owners and their information requirements for BIM models they have established from the construction to the operations stage of a facility. This study focused on BIM use and handover requirements for operations and maintenance of facilities on university and college campuses in the mid-Atlantic region of the United States. Reflections from this study should be applicable for both O&M stages in the USA and UK respectively.

Background

Building Information Model (BIM), as defined in the National BIM Standard – United States® Version 3 is the digital representation of physical and functional characteristics of a facility. As such it serves as a shared knowledge resource for information about a facility, forming a reliable basis for decisions during its life cycle from inception onwards (National BIM Standard, 2015). Facility owners and managers rely on trusted asset data developed during projects in BIM for reducing risk in operations, strategic planning, design, construction, sustainability, and environmental responsiveness (Massport, 2015). In general, owners should review their current information needs for operations and maintenance and establish data requirements that support those needs. At a minimum, major equipment should be described by facility attributes such as make, model, manufacturer, and serial number. Additional attributes include warranty information, parts lists, maintenance schedules, and manufacturer contact information would further contribute to asset management if included with the handover (NIBS, 2017). International Standard Organization (ISO) 55000 defines asset management as the coordinated activity of an organization to realize value from assets. Furthermore, asset management achieves business objectives through asset-related decisions, plans, and actions within a strategic framework of processes, techniques, and tools. It seeks to optimize the cost, risk and performance of assets over their lifecycle at an individual asset, asset system, and asset portfolio level (International Standards Organization, 2014). BIM based asset management is a process in which project data is linked to a Record Model, delivered at project handover, to aid in the maintenance and operation of a facility and its assets. These assets, consisting of the physical building, systems, surrounding environment, and equipment (NIBS, 2017).

Handover

According to Joroff and Project (2000), there are four roles associated with four phases of operations and maintenance (O&M) during a facility's lifecycle: 1) strategy making (policy maker), 2) controlling (controller), 3) deal making (user), and 4) task managing (technical manager), with data flowing continuously between all four. This information flow is often the difficulty that exists in a large FM organization. Most of the data needed for the O&M stage is created during the design and construction stages (Smith and Tardiff, 2012). Before this data can be used in the O&M stage it often has to be modified, mainly due to user interventions. Typical activities completed during O&M include portfolio management, asset management, property management, and service management (Schraven, Hartmann, and Dewulf, 2011). Asset management focuses on the implementation of a building plan for the owner to realize the lifecycle value from the building assets (The Asset Management Institute, n.d.).

The information provided will be used for the O&M stage and the lifecycle of the building. Prior research reported industry professionals deal with two types of data, structured and unstructured (Mayo and Issa, 2015). Typically, unstructured data can be in paper or digital format, which owners and their FM teams often receive in an unorganized and incomplete manner. Warranty information, equipment manuals, and manufacturer information, are a few examples of unstructured data currently provided from construction to FM teams. Structured data examples include construction drawings, project manual, and various spreadsheets containing project information. Therefore, structured data is any type of organized data from the project. However, all this data must typically be “unpacked” by the facility owner to make it accessible to be used for the O&M phase. There are instances where early planning for handover data is done to provide the owner with a means for quicker upload of data to the owner’s Integrated Workplace Management System (IWMS) or Computerized Maintenance Management Software (CMMS). In the past, the facility handover procedures from construction did not provide owners with the confidence and assurance that they were receiving the data needed to operate and maintain the facility at optimum performance. To resolve this issue the industry has slowly implemented strategies and tools for handover data to ensure owners receive the data they need. These strategies and tools include utilizing open standards (i.e., IFC and Information Delivery Model (IDM), AIMs (Asset Information Models), Owners Project Requirements (OPR), and Building Information Modeling to name a few. The literature review revealed that the BIM model is currently being used by the FM team primarily for space management, asset management and reporting on volumetric needs such as HVAC/room volumes.

Methodology

This research was approached with a broad perspective to identify the state-of-practice of BIM data use for Facilities Management (FM) and to review the importance of specific data. The aim of this study was to answer the following two research questions.

- Why is project data handover vital to facilities management for operations and maintenance?
- How is project data collected and used for facilities management purposes?

An electronic survey link with an overview of the purpose of this study was sent to 284 individuals in the role of facility owners, facility managers, or similar positions at university campuses in the mid-Atlantic region of the United States. The level of BIM use and competencies of individuals was unknown when the recruitment email was distributed. The survey contained 23 questions, which were divided into six sections designed to review the overall state-of-practice for O&M by facilities managers.

- Section 1: BIM Personnel – asked about dedicated BIM roles and BIM related leadership roles in the organization
- Section 2: BIM Requirements – included questions about the percentage of projects where BIM is used, BIM adoption, and BIM requirements created by the organization.

- Section 3: Construction Deliverables – were questions related to the timing of asset data collection, validation of the data collected, formats of requested handover deliverables, and types of BIM deliverables mandated by the organization.
- Section 4: Facility Management – asked questions about the timing of BIM model reviews, QA/QC procedures for model-based deliverables, the format most frequently used by FM teams for referencing data needs, floor plan use, time spent on final BIM deliverable to make it useable, most common reasons why building documentation is not collected, and the importance of BIM for the O&M stage.
- Section 5: Visualization & Asset Management – asked about visual formats useful for O&M tasks, protocols, role responsible for providing the data. to the facility owner.
- Section 6: Demographics – questions related to the participants' role and organization

The response rate was 21%, with 59 participants in total recorded. However, some early feedback provided an indication that the survey may not have reached many facility owners experienced with BIM use, and therefore, some participants may not have been able to fully understand or answer some of the questions. Due to the page limitations for this paper, the results discussed are limited to Section 3: Construction Deliverables and Section 4: Facilities Management.

Results

Construction Deliverables

The survey included three questions specific to construction deliverables and associated requirements. First, participants were asked how they collect and/or check asset data during construction. It is assumed that the 19 that did not answer are unsure if and how asset data is collected or checked during construction. The answer choice with the highest frequency was "Excel Spreadsheet." The next highest frequency was "BIM360 spreadsheet (native inside BIM360)," with a frequency of 10 whereas "Excel Spreadsheet" had just over double that amount at a 25 frequency of use that was reported by the 59 participants. Prior research established the current practice of using spreadsheets as the common format in either a .csv of .xml file type for construction to handover for transference of data into FM systems (Lucas and Addagalla, 2017). After integration with the current CMMS, it was revealed that the result exceeded the expectations of FM technicians, with a 20% reduction in the time needed for corrective action by providing quick access to floor plans and data. It also reduced risk associated with emergency events by developing "what if" scenarios. These are examples of the benefits realized with the handover of structured data. Figure 1 displays the total of participants responses to the question.

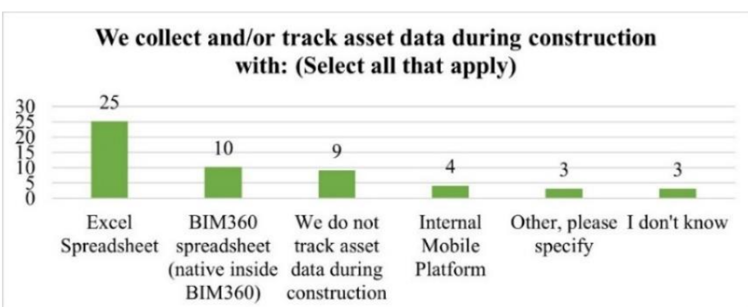

Figure 1 Asset data collection tools

In figure 2 both the "BIM model" and "Electronic" was indicated as the deliverable required for handover. Electronic could mean different things, such as paper formatted documents and information handed over on a jump drive, or a model, therefore it is unclear if there is overlap in responses. In hindsight, for this answer choice, a better option may have been to allow the participant to have an "input text option" as having "Electronic" is too broad of a choice. Comparing the frequency for "Spreadsheets" of 19 for this question to the question about tracking asset data during construction which had "Excel Spreadsheet" receiving 25 counts could be interpreted multiple ways and once again could result in duplicate of the responses for both questions.

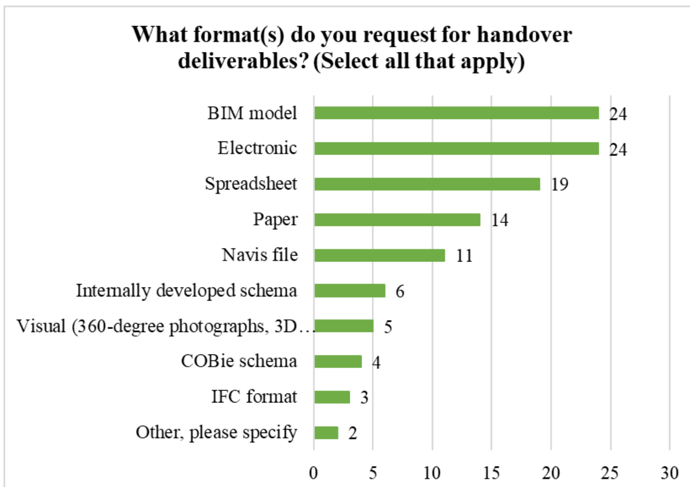

Figure 2 Format for handover deliverables

The final question pertaining to construction deliverables asked about what deliverables are mandated. To be clear, this does not imply that the organization is "using BIM" for O&M as some owners may get the models but not actually use them. However, this is a good indication of the percentages of those who have started mandating a model. One participant added, "Record documents are required, the Project Management leadership fails at not placing responsibility into the contract, as to who is responsible for update and turnover." This statement also validates the literature findings and is a recurring theme - which ties to the support of the leadership, and to the difficulty of implementation due to so many siloed roles in FM.

Table 1

Question	Answer choices available to select from		
Q12 – What types of BIM deliverables are mandated by your organization at construction handover? (select all that apply)	No specific model deliverable has been mandated	15.66%	13
	As built models provided by design team	21.69%	18
	As-built models provided by construction team	22.89%	19
	A populated COBie spreadsheet	1.20%	1
	A populated spreadsheet from contractor	13.25%	11
	Other, please specify	6.02%	5
	Record Model from design team	19.28%	16

Facilities Management

To review the current state-of-practice with regards to O&M staff and document use, the next question inquired about the different formats used. Literature has continually surmised that Revit is not a platform that can be used widely by field personnel due to a lack of BIM skills, but there were 13 responses that revealed something different. The most widely used format is still CAD, indicating that many are still hanging on to the traditional methods of space management and building documentation. Since this question also included the option to select all that apply, most of the responses include three or more format types, most likely due to the overlap in questions regarding IWMS, CMMS and CAFM systems and additionally, the need that many organizations must maintain hard copies of as-builts. However, one participant indicated that they utilize scanned (pdf) plans. Frequency of responses by question are shown in Figure 3.

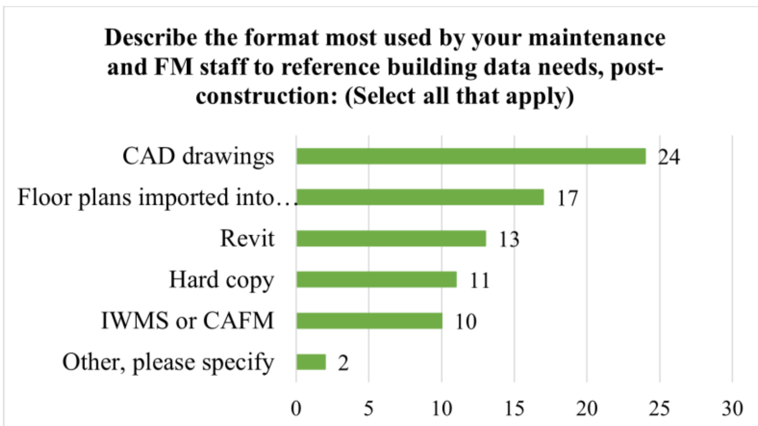

Figure 3 Post-construction data format for O&M

When asked how they will utilize the final deliverable(s) post construction, the answer choice with the highest frequency, at 25%, was “We do not currently use the model or its attribute data post construction,” which means the model is not being used for O&M. The reason it is not used for O&M could be one of the many BIM implementation issues identified in the literature review, such as, lack of trained in-house personnel, lack of standards, interoperability issues, or other. Previous research has shown that BIM can be used as an information container, assist in decision making, be integrated with CMMS, CAFM and/or IWMS. Some facility owners have successfully implemented BIM for O&M. The second highest frequency answer choice was, “We utilize the model(s) attribute data to track space management” with “We utilize the model and/or its attribute data to track asset management” being a close second. The literature review discovered that space management and asset management are two ways to utilize BIM. As previously stated, owners can utilize an owner’s project requirement (OPR) to ensure they are provided with the needed data for optimum O&M of the facility. One participant commented that “We have linked 3D geometric aspects of the model with hyper-linked close-out documentation.” Two participants selected “I am not sure” and two participants selected “Other, please specify.” The participants selecting the latter input the following:

- “Future existing conditions”
- “Models currently not in use, but plan to integrate GIS, CAFM, and maintain for distribution of existing condition records”

Most of the feedback illustrates that firms know BIM for O&M is the future but may not or have not reached that point yet. One participant stated that when it comes to O&M and BIM, they receive models at handover but have no way to update them or distribute them as they have no dedicated staff or proficiency for this task. Furthermore, it was stated that the design and construction teams extract the construction documents and conduct analysis throughout the project and the organization archives the “derivative materials.”' This question should have contained a “none of the above” answer choice, which may have resulted in a higher frequency for this question.

Previous research stated that BIM output is typically limited to 2D data as users cannot see, handle or deal with any other data format due to a lack of knowledge of the various data formats (Bosch, Volker, and Koutamanis, 2015). Figure 4 shows the amount of time dedicated to organizing the BIM data after handover to make it usable for their organization. The time spent on making data useable could possibly be decreased to less than 3 weeks if the organization required an Information Delivery Model (IDM), an Owner Project Requirement (OPR), and/or open standards. An IDM is a model detailing lifecycle processes of assets, including data requirements for all processes to be completed (NIBS, 2017). An OPR guides the Owner on project execution as well as forming a basis for measuring all activities and products during decision making throughout the facility’s lifecycle addressing form, time, budget, and function (NIBS, 2017). Open standards are data standards that are compatible and useable across a wide range of hardware and software platforms.

Figure 4 Time to organize data after handover

Discussion and Conclusion

Evident from the literature and study results, the state-of-practice for BIM data handover from construction to operations for asset management varies by owner and facility type. This study focused on university/college campuses in the mid-Atlantic region of the United States. While it revealed widespread differences in the participants requirements for handover data, approximately half of all participants require or receive the data in a BIM format. It also indicated that the majority of FMs spend a month or more organizing the BIM data to make it usable after handover. In figure 6 the ISO 19650 information management process is shown. The process includes the preparation of information requirements, review of prospective parties in relation to information management, initial and detailed planning for how and when information will be delivered, and review of information deliverables against the information requirements before they are integrated with operational systems.

The process is detailed in its requirements but should be applied in a way that is appropriate based on the scale and complexity of the project or asset management activities.

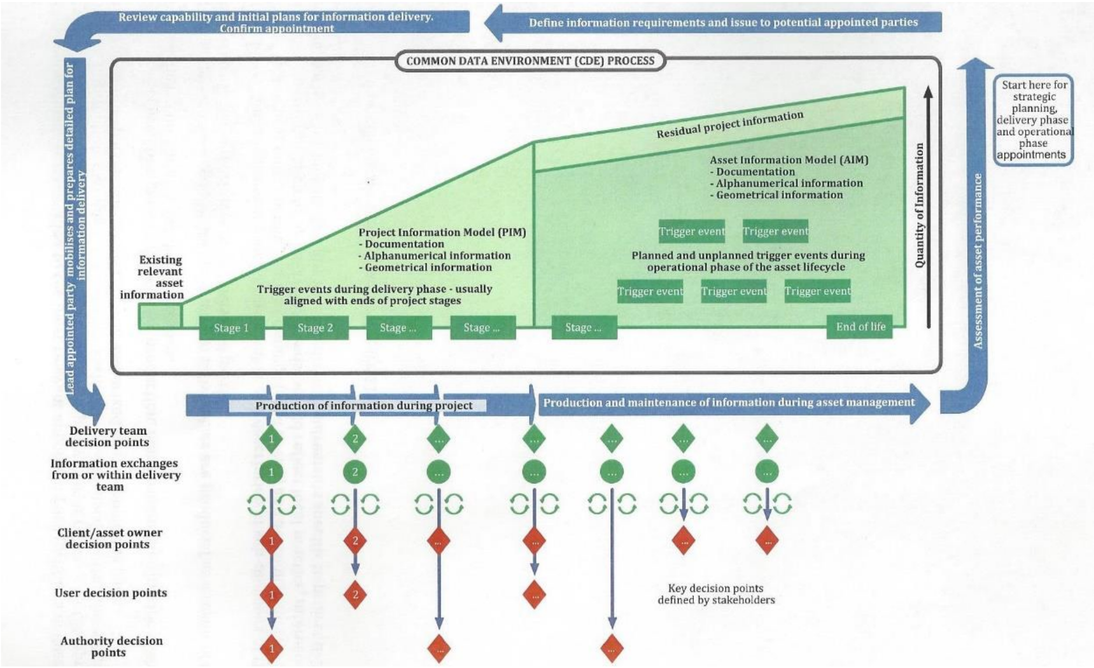

Figure 6 ISO 19650 information management process (ISO 19650, Part 1, 2018, p.28)

Figure 6 shows a potential solution to some of the issues identified in this paper. Following a prescribed process for understanding O&M needs has been defined in the UK for some years. Whatever process is followed it is imperative that the owner fully understands their information needs to effectively run their facilities. Understanding the issues identified in this paper is a great starting point. Using BIM to monitor the development of the information needed to run a facility is clearly a key enabler. BIM and a recognized information flow are both needed for an owner to fully use new technologies to better manage their facilities.

References

Bosch, A., Volker, L., & Koutamanis, A. (2015). BIM in the operations stage: Bottlenecks and implications for owners. *Built Environment Project and Asset Management*, *5*(3), 331–343. https://doi.org/10.1108/BEPAM-03-2014-0017

Cavka, H. B., Staub-French, S., & Poirier, E. A. (2017). Developing owner information requirements for BIM-enabled project delivery and asset management. *Automation in Construction*, *83*, 169–183. https://doi.org/10.1016/j.autcon.2017.08.006.

Bechtel BIM, 2014. Gatwick Airport BIM Projects, https://www.youtube.com/watch?v=3sEU3BGtxho

Hulse, Rod & Codd, Andy & Neath, Stephanie (2014). Building information modelling in practice: Transforming Gatwick Airport, *UK. Proceedings of the ICE - Civil Engineering*. 167. 81-87. http://dx.doi.org/10.1680/cien.13.00018

International Standard Organization (2018). ISO19650-1:2018, https://www.iso.org/standard/68078.html

International Standard Organization (2014). ISO55000:2014, https://www.iso.org/standard/55088.html

Joroff, M. L., & Project 2000, C. R. E. (1993). Strategic Management of the Fifth Resource: Corporate Real Estate. Industrial Development Research Foundation. https://books.google.com/books?id=bcp9twAACAAJ.

Lucas, J., & Addagalla, S. E. (2017). *Building Information Modeling Implementation for Facilities Management on U.S. University Campuses*. 9.

Mallela, Blackburn, Grant, Kennerly, Petros, & Yew (2020). Building Information Modeling (BIM) Practices in Highway Infrastructure: FHWA Global Benchmarking Program Report, Federal Highway Administration U.S. Department of Transportation.

Massport (2015). *BIM Guidelines for Vertical and Horizontal Construction, Massachusetts Port Authority*. http://www.massport.com/business-with-massport/capital-improvements/resource-center/

Mayo, G. and Issa, R. (2015) Nongeometric Building Information Needs Assessment for Facilities Management. *Journal of Management in Engineering*, 32(3):040115054. DOI: 10.1061/(ASCE)ME.1943-5479.0000414

National Institute of Building Sciences (2015). National BIM Standard – United States ® Version 3, https://www.nationalbimstandard.org/nbims-us-v3

National Institute of Building Sciences (2017). National BIM Guide for Owners, https://www.nibs.org/files/pdfs/NIBS_BIMC_NationalBIMGuide.pdf

Schraven, D., Hartmann, A., and Dewulf, G. (2011). Effectiveness of infrastructure asset management: Challenges for public agencies. *Built Environment Project and Asset Management*, *1*(1), 61–74. https://doi.org/10.1108/20441241111143786.

Smith, D. K., & Tardif, M. (2012). Building Information Modeling: A Strategic Implementation Guide for Architects, Engineers, Constructors, and Real Estate Asset Managers. John Wiley & Sons.

The Institute of Asset Mangement (n.d.). https://theiam.org.

Comparison of State Department of Transportation Practices in Analyzing Risks for Large Infrastructure Projects

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Construction projects are inherently associated with various risks that can increase the project costs. Identifying and analyzing such risks are essential to successfully managing construction budgets at state Departments of Transportation (DOTs). While many state DOTs have developed and/or adopted risk assessments methodologies and tools, Tennessee DOT (TDOT) lacks a comprehensive methodology and tool to analyze construction project risks. This study reviewed state DOT practices of analyzing various risks associated with large infrastructure construction projects. The comparison of risk assessment practices among state DOTs are summarized in three sections: a) risk management, b) major categories affecting project costs, and c) risk estimating tools and practices. The review finds that many state DOTs have similar practices of analyzing project risks and have developed spreadsheet-based tools to automate such analysis. While some risk analysis tools are used primarily for qualitative risk analysis, other tools are developed for qualitative and quantitative risk analysis. Such tools with qualitative and quantitative risk analysis can be used to quantify contingencies for various projects for budgeting purposes.

Keywords: risk-based-cost-estimation, risk-analysis, risk-factors, Monte-Carlo-Simulation

Introduction

The Project Management Body of Knowledge (PMBOK®) Guide defines risk as “an uncertain event or condition that, if it occurs, has a positive or negative effect on one or more project objectives” (Project Management Institute (PMI), 2017). Issues are risks that becomes a reality. Ideally, all negative risks should be avoided, but some risks cannot be avoided. As such, project stakeholders need to be prepared to assess the potential impacts of the risks that can become a reality. Thus, various risk assessment techniques and tools are developed by various organizations including state Departments of Transportation (DOT). For state DOTs, various project risks such as unexpected site conditions can dramatically increase the project costs, duration, and complexity. If such risks are not identified and analyzed during the planning phase, they can have ripple effect in state DOT’s construction budget management. For example, if a project cost overruns its initial budget, other projects may be delayed or removed from the fiscal year plan, the project itself may be halted, or the scope of the project may be reduced. If a project cost underruns its initial budget, them remaining budget may be unused and potentially frozen or claimed back by the federal government. Thus, proper risk analysis is essential to optimize the use of available budget in state DOTs. However, Tennessee DOT (TDOT) currently lacks a comprehensive methodology and tool to analyze various risks and their potential cost impacts. As such, this study reviews existing literature on various risk analysis methodologies and tools developed and used by other state DOTs.

Background

Several studies have identified and classified major factors affecting construction cost overruns such as poor estimating, engineering and construction complexities, scope changes, market conditions, unforeseen conditions, and faulty execution (AASHTO, 2013; Gransberg et al., 2015; Schexnayder et al., 2009; Washington State Department of Transportation, 2014). The theories of risk-based estimating can be applied to produce more reliable estimates (Kermanshachi & Safapour, 2020). Some states have already taken initial steps to towards implementing risk-based estimating in their business practices (Ashuri et al., 2015; California Department of Transportation, 2012; Nevada Department of Transportation, 2012; New York State Department of Transportation, 2009; Shane, 2015; Texas Department of Transportation, 2015; Washington State Department of Transportation, 2014).

Risk Based Cost Estimating

According to AASHTO Guidebook (2013) risk-based estimating combines traditional estimating methods for known items and quantities with risk analysis techniques to estimate uncertain items, uncertain quantities, and risk events. The risk-based portion of the estimate typically focuses on a few key elements of uncertainty and combines Monte Carlo sampling and heuristics to rank critical risk elements. This approach is used to establish the range of total project cost and to define how contingency should be allocated to critical project elements.

Several studies have been conducted to aid state highway agencies in implementing risk-based estimating practices (Gransberg et al., 2015; National Academies of Sciences, 2017; Schexnayder et al., 2009). These includes theoretical framework and practical tool developments. DOTs from states such as Georgia, Texas, Washington, New York, and California have also developed guidebooks and tools highlighting the importance of considering various types of risks in project development phases using risk register, influence diagram, Monte Carlo Simulation, and risk mitigation for major projects (Ashuri et al., 2015; California Department of Transportation, 2012; New York State Department of Transportation, 2009; Texas Department of Transportation, 2015; Washington State Department of Transportation, 2014).

Some additional relevant studies include Chen et al. (Chen et al., 2020) that introduced a qualitative and quantitative methods based on risk allocation in a probabilistic Monte Carlo simulation. Sadeh et al. (2021) introduced a new model to evaluate and assess risk in terms of cost impact, utilizing a fuzzy Monte Carlo simulation approach for the first time. The method consists of ranking the top risks using a fuzzy logic system utilized in an objective manner by setting criteria for experts to rank the risk based on cost impact and probability to reduce human biases, then evaluating their cost impact through a Monte Carlo simulation both pre- and post-mitigation. Gündüz et al. (2013) identified 81 delay factors on construction projects, analyzed these factors with the relative importance index method, and provided recommendations to minimize and control delays in construction projects.

Tomek and Matějka (2014) and Zou et al. (2017) reviewed impacts of BIM in managing construction risks by comparing traditional risk management methods with BIM technologies and concluded that BIM, as a tool for risk management, is still in its infancy.

Although the existing studies have attempted to identify and evaluate the project risks, most of them focus primarily on the cost growth during the construction phase. However, one of the major reasons of cost growth over time are changes in scope and specification that occur before the construction. As such, a study needs to be conducted to evaluate the cost growth over the project development from the conceptual phase to the construction phase so that the TDOT management team can make more informed budgeting decisions.

Methodology

This study was guided by the research question: what is the state of practice among state DOTs in analyzing risks in large infrastructure projects? To answer this question, we utilized a systemic method to identify various DOT practices related to risk analysis and risk-based estimating. First, the authors reviewed cost estimation processes and practices of several states by visiting the DOT websites. The information of the DOT websites was the main basis for this comparative study. Next a through literature search was conducted focusing on published journal articles, reports, and conference proceedings on the topic. The literature review identified several major areas of similarities and contrasts which are presented in this paper.

Comparison of Risk Assessment Practices Among State DOTs

This section summarizes existing studies on risk analysis for large infrastructure projects and provides a) an overview of current practices for risk management, b) major categories of risk factors affecting construction projects, and c) overview of current risk estimation tools and practices.

Risk Management

State DOTs have many similarities in risk management for construction projects. For example, state DOTs have common tasks associated with risk analysis: a) risk registers, b) risk analysis, c) risk response, and d) risk monitoring and control (Shane, 2015; Texas Department of Transportation, 2015). Risk registers are frequent practice for any construction company, public or private. Risk registers are basic notes on the risk which include cost, likelihood, and date. Most existing risk quantification tools create the risk register automatically based on the user's inputs. Many state DOTs have developed spreadsheet-based tools to analyze project risks. State DOTs have recommended various tools to analyze risk and determine contingencies such as Monte Carlo Analysis, Probability x Impact Matrix (P x I), and Crawford Slip Method. Risk response can be one of the four: avoid, mitigate, accept, or transfer. Finally, risk monitoring and control acts as a feedback loop to improve the risk management process.

Major Categories Affecting Project Costs

The categories in which risk factors may be divided into two generic types. The first type involves a more conceptual determination and is mostly found in academia. These may include external risks, internal risks, enterprise risks, program risks, and project risks (D'Ignazio et al., 2011). External risks are risks that are unavoidable and an example of this may be inclement weather delays. Internal risks are risks specific to the project itself. Enterprise risks are risks amongst the design staff of the project. Program risks are risks generated by upper-level management, and an example of this may be the breakdown of communication between management and the workers on site. Project risk are risks from the workers at the site and an example of this may be noncompliance with safety protocols.

The second type of classification are risks classified by more tangible and realistic issues seen on large infrastructure projects. The most important of these risks is right of way. There are countless department of transportation studies around the costs associated with this, and it is by far the most researched. Right of way risks are any costs to acquire the land around projects. These costs are especially prevalent in large highway projects. The value of the land, court costs (Cox, 2016), and negotiation are all examples of right of way costs (Tennessee Department of Transportation, 2021). Even when the academic classifications are used, right of way remains a top risk priority (Georgia Department of Transportation, 2020). Another important risk factor are geotechnical issues. Soils are typically tested in increments of ten feet or more, which may leave gaps in the soil tests. Then, upon excavating the soil, hidden issues are uncovered, which will cause schedule and monetary changes. Another interesting factor is payment and contract structure (Michigan Department of Transportation (MDOT), 2015). A time and materials contract would shift risk to the owner because any schedule delays come directly from the owner's budget.

The other risk factors that present in several other DOT articles were environmental, right of way (Abd El-Karim et al., 2017), utilities, public information, third party agreements, drainage, traffic handling, design, and other (Missouri Department of Transportation, 2022). These are the risk factors affecting preconstruction that need to be quantified in this study because these tangible factors are focused on by every state DOT.

Risk breakdown structure is a way of further breaking down these risks. It is similar a flowchart with the nine risks at the top, and the examples of each are the subsequent boxes under each risk.

Risk Estimation Tools and Practices

To effectively identify how states are quantifying and using risks factors, a further look into current estimation practices is required. Tennessee's unique geographic position and political agendas create an individual set of risk factors. To gain insight into these, the eight states that border Tennessee were evaluated for their cost estimation techniques. Their proximity allows for a similar set of risks and needs for construction projects on a state governmental level. Alabama, Missouri, and Kentucky had no readily available information on their cost estimation procedures. North Carolina (Kluckman, 2021), Georgia (Georgia Department of Transportation, 2019), and Mississippi (Mississippi Department of Transportation, 2017) all used cost-based estimation for heavy civil construction. It is important to note that cost based is simply the final form of estimation, and that each line item is evaluated based on the estimator's experience or the historical data. Naturally, historical data has some of the risk factors built into them, but there is no way to isolate each risk and quantify it. For instance, if a project encountered risks X, Y, and Z and the budget ran over by two million, the next project that uses this historical data will already have X, Y, and Z allocated for in its budget. Virginia uses RS Means as a basis for all construction estimates (Virginia Department of Transportation, 2012). The main advantage to using RS Means is that it is the most up-to-date cost data, so it can account for external risks.

Most state departments of transportation are very conservative with their risk-based estimation software and tools, so information is lacking on practices across the board. However, leading state

DOTs, such as Washington, California, Nevada, and Montana have limited information available to the public. Washington is ahead of the curve as they already have an Excel based tool and user manual (Washington State Department of Transportation, 2022). This manual incorporates a Monte Carlo simulation to find the most likely costs as well as other advanced statistics measures to quantify risks. The main disadvantage to this Excel file is it is incredibly complex to use, and the average construction estimator would have to train from months to become accustomed to it. The goal of the tool for TDOT is an Excel file that can be taught in a reasonable timeframe. Additionally, there are no quantities associated with certain risks, all those values are input on a project-by-project basis, which is not standardized. Standardization of risk factors and their respective markup factors is another important goal of this study, however the probability of each risk factor occurring may be input into the tool by the user or calculated with a Monte Carlo simulation. The Nevada DOT uses a Monte Carlo simulation for their risk-based estimates as well (Nevada Department of Transportation, 2021).

"A Stochastic Three-Dimensional Cost Estimation System for Hot Mix Asphalt in the State of Alabama" goes about evaluating probabilities of risks another way using percentage errors (Karen Xu, 2018). This article takes each contractors' itemized bids and compares them to the state's estimate. For each bid, the actual value of the construction was compared to each line item, and the line item with the highest percentage error is the most influential risk factor.

In summary, the Monte Carlo simulation is the most popular way of evaluating the probability and potential impact of risk factors. Excel based tools are the best as they are readily available in most offices, relatively cheap compared to dedicated software, and most people know how to use Excel.

Conclusion

This study reviewed state DOT practices of analyzing various risks associated with large infrastructure construction projects. The study finds a wide variety of practices and tools utilized to analyze project risks. The comparison of risk assessment practices among state DOTs were summarized in three sections: a) risk management, b) major categories affecting project costs, and c) risk estimating tools and practices. Many state DOTs follow similar risk management approaches consisting of four steps. Many state DOTs have already developed and implemented various risk analysis tools. Some state DOT tools are capable of qualitative analysis only while other tools are capable of both qualitative and quantitative analysis. Quantitative tools can be used for estimating contingencies for project costs. Major categories affecting project costs includes external risks, internal risks, enterprise risks, program risks, and project risks. Most state DOTs have excel based tools for risk estimating.

References

AASHTO. (2013). *Practical Guide to Cost Estimating* (First).

Abd El-Karim, M. S. B. A., Mosa El Nawawy, O. A., & Abdel-Alim, A. M. (2017). Identification and assessment of risk factors affecting construction projects. *HBRC Journal*, *13*(2), 202–216. https://doi.org/10.1016/j.hbrcj.2015.05.001

Ashuri, B., Kingsley, G., Rogers, J., Gahrooei, M. R., Ilbeigi, M., Sung, E. J.-Y., Toroghi, S. (Sean) H., & Georgia Institute of Technology. (2015). *Streamlining project delivery through risk analysis.* (FHWA-GA-15-1305). https://rosap.ntl.bts.gov/view/dot/29370

California Department of Transportation. (2012). *Project Risk Management Handbook: A Scalable Approach*. http://www.dot.ca.gov/hq/projmgmt/documents/prmhb/PRM_Handbook.pdf

Chen, L., Lu, Q., & Zhao, X. (2020). Rethinking the Construction Schedule Risk of Infrastructure Projects Based on Dialectical Systems and Network Theory. *Journal of Management in Engineering*, *36*(5). https://ascelibrary.org/doi/10.1061/%28ASCE%29ME.1943-5479.0000829

Cox, D. (2016). *GDOT Planning Level Cost Estimation*. Risk Based Peer Exchange. https://winter.codot.gov/business/eema/assets/2016-1/cdot-rbce-peer-exchange-files/ga-pres-co-rbce-peer-exchange-may-2016.pdf

D'Ignazio, J., Hallowell, M., & Molenaar, K. (2011). *Executive Strategies for Risk Management by State Departments of Transportation* (NCHRP Project 20-24, Task 74). Article NCHRP Project 20-24, Task 74. https://trid.trb.org/view/1515811

Georgia Department of Transportation. (2019). *Programmed Construction Cost Estimate QC-QA Best Practices*. https://www.dot.ga.gov/PartnerSmart/DesignManuals/EngineeringServices/Programmed%20Construction%20Cost%20Estimate%20QC-QA%20Best%20Practices.pdf

Georgia Department of Transportation. (2020). *Guide to Mitigating GDOT Schedule Risks*. Georgia Department of Transportation. https://www.dot.ga.gov/AboutGeorgia/Offices/Documents/ProgramDelivery/ProjectManagerandDesignPhaseLeaderGuide-ScheduleRiskMitigation.pdf

Gransberg, D. D., Jeong, H. D., Craigie, E., Rueda, J., & Shrestha, J. (2015). *Preconstruction Services Cost Estimating Guidebook* (NCHRP Project 15-51). Federal Highway Administration.

Gündüz, M., Nielsen, Y., & Özdemir, M. (2013). Quantification of Delay Factors Using the Relative Importance Index Method for Construction Projects in Turkey. *Journal of Management in Engineering*, *29*(2), 133–139. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000129

Karen Xu. (2018). *A Stochastic Three-Dimensional Cost Estimation System for Hot Mix Asphalt in the State of Alabama* [Auburn University]. https://etd.auburn.edu/bitstream/handle/10415/6213/Keren%20Xu_Thesis%2004.30.2018.pdf?sequence=2

Kermanshachi, S., & Safapour, E. (2020). Gap Analysis in Cost Estimation, Risk Analysis, and Contingency Computation of Transportation Infrastructure Projects: A Guide to Resource and Policy–Based Strategy Establishment. *Practice Periodical on Structural Design and Construction*, *25*(1), 06019004. https://doi.org/10.1061/(ASCE)SC.1943-5576.0000460

Kluckman, R. (2021). *NCDOT Conceptual Construction Cost Estimation Guidelines*. North Carolina Department of Transportation. https://connect.ncdot.gov/projects/Roadway/RoadwayDesignAdministrativeDocuments/NCDOT%20Conceptual%20Construction%20Cost%20Estimation%20Guidelines.pdf

Michigan Department of Transportation (MDOT). (2015). *Innovative Construction Contracting Guide*. https://www.michigan.gov/mdot/-/media/Project/Websites/MDOT/Business/Contractors/Innovative-Contracting/Innovative-Construction-Contracting-Guide.pdf?rev=ac8c5463efac422f9d55aeb66a8e64a2&hash=872ED46A8403CFD5A63BF41F63D51E1F

Mississippi Department of Transportation. (2017). *Construction Manual*. Mississippi Department of Transportation.

Missouri Department of Transportation. (2022). *Category:149 Project Delivery Determination and Initial Risk Assessment*. https://epg.modot.mo.gov/index.php/Category:149_Project_Delivery_Determination_and_Initial_Risk_Assessment

National Academies of Sciences, E. (2017). *Applying Risk Analysis, Value Engineering, and Other Innovative Solutions for Project Delivery*. https://doi.org/10.17226/24851

Nevada Department of Transportation. (2012, August). *Risk Management and Risk-Based Cost Estimation Guidelines*. http://nevadadot.com/uploadedFiles/NDOT/Documents/RBE_Guidelines_Final_2012_August.pdf

Nevada Department of Transportation. (2021). *Risk Management and Risk-Based Cost Estimating Guidelines*. Nevada Department of Transportation. https://www.dot.nv.gov/home/showpublisheddocument/4518/637637657516400000

New York State Department of Transportation. (2009). *Risk Management for Project Development*. https://www.dot.ny.gov/divisions/engineering/design/dqab/dqab-repository/Risk%20Management%20for%20Project%20Development%20Guide_Final%20Draft_010514.pdf

Project Management Institute (PMI). (2017). *A Guide to the Project Management Body of Knowledge (PMBOK® Guide)*. Project Management Institute (PMI).

Sadeh, H., Mirarchi, C., & Pavan, A. (2021). Integrated Approach to Construction Risk Management: Cost Implications. *Journal of Construction Engineering and Management*, *147*(10), 04021113. https://doi.org/10.1061/(ASCE)CO.1943-7862.0002140

Schexnayder, C. J., Molenaar, K. R., Anderson, S. D., Transportation Research Board, National Cooperative Highway Research Program, & Transportation Research Board. (2009). *Procedures Guide for Right-of-Way Cost Estimation and Cost Management* (p. 14289). National Academies Press. https://doi.org/10.17226/14289

Shane, J. S. (2015). *Risk-Based Engineers Estimate*. 69.

Tennessee Department of Transportation. (2021). *Right-of-Way Procedures Manual*. Tennessee Department of Commerce & Insurance. https://www.tn.gov/content/dam/tn/tdot/right-of-way-division/ROW_Procedures_Manual.pdf

Texas Department of Transportation. (2015). *Risk-Based Construction Cost Estimating*. 286.

Tomek, A., & Matějka, P. (2014). The Impact of BIM on Risk Management as an Argument for its Implementation in a Construction Company. *Procedia Engineering*, *85*, 501–509. https://doi.org/10.1016/j.proeng.2014.10.577

Virginia Department of Transportation. (2012). *Guidelines and Procedures for Estimating and SAAP Section*. Virginia Department of Transportation.

Washington State Department of Transportation. (2014). *Project Risk Management Guide*. http://www.wsdot.wa.gov/publications/fulltext/cevp/ProjectRiskManagement.pdf

Washington State Department of Transportation. (2022). *Project Risk Analysis Model*. Washington State Department of Transportation.

Zou, Y., Kiviniemi, A., & Jones, S. W. (2017). A review of risk management through BIM and BIM-related technologies. *Safety Science*, *97*, 88–98. https://doi.org/10.1016/j.ssci.2015.12.027

Wearable Robot Acceptance: Understanding the Impact of Trialability on User Perception

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The use of emerging technologies such as Wearable Robots (WRs) or exoskeletons has gained considerable attention in the construction industry in recent times. WRs or exoskeletons augment workers' physical capacity when performing physically demanding tasks. While there is growing interest in exoskeletons, existing literature suggests that some workers oppose WR use on job sites. This resistance is largely driven by second-hand information gathered through multiple channels, and not based on actual use. Therefore, it is important to assess how hands-on experience (trialability) influences the end-user perception of the use of exoskeletons. To fill this gap, the researcher utilized a mixed-method approach consisting of a structured literature review, controlled experiment, and surveys (pre-post experiment surveys). Statistical analyses revealed that in most cases, trialability had a positive influence on technology acceptance constructs assessed (including “Behavioral Intention to Use”), confirming the important role of hands-on experience in exoskeleton integration research and practice.

Key Words: Exoskeleton, Wearable robots, Technology acceptance, Trialability

Introduction

The management of occupational safety and health in the construction industry faces unique challenges. These challenges result in part from the dynamic work environments of construction, the frequent use of heavy equipment, and the unavoidable worker-hazard interactions (Hallowell & Gambatese, 2009). As part of efforts to improve construction safety performance, researchers have reported that the application of safety technologies within various phases of construction projects will significantly enhance the safety and health of construction workers (Guo et al., 2017; Nnaji & Karakhan, 2020). Of these technologies, Wearable Robotics (WRs) has been gaining considerable attention in the construction industry in recent times (Antwi-Afari et al., 2021; Okpala et al. 2022a). The potential benefits of WRs for safety and productivity improvements have been covered in safety research (Kim et al., 2019; Okpala et al. 2022a; Zhu et al., 2021). Although WRs have the potential to significantly reduce work-related musculoskeletal disorders (WMSDs) and the attendant losses associated with accidents (Gonsalvez et al. 2021; Antwi-Afari et al., 2021), this reduction is only possible when workers truly perceive WRs’ utility and decide to use the device during work. However, existing literature suggests that the use of wearable devices in the construction industry is relatively low (SmartMarket Report, 2021; Okpala et al., 2020). For workers to appreciate the potential utility of exoskeletons, they should take part in the decision-making process and be allowed to test these technologies before they are integrated into work operations.

According to the Innovation Diffusion Theory, the concept of trialability (i.e., trying out an innovative technology) is critical to driving the successful integration of an emerging solution (Sahn, 2006). Fundamentally, it is posited that information from end-users will provide critical information that will enable the technology to be developed and implemented in such a way that the expectations of end-users are satisfactorily met (Elprama et al., 2022). User experience is very important in examining technology acceptance (Choi et al., 2017) leading to user-centered work designs (Shore et al., 2018) and productive appraisals of the effects of the WRs being introduced to the workplace (Kermavnar et al., 2021). However, little to no studies within the construction domain have examined the impact of trialability of the acceptance of WR in the construction industry. Moreover, the concept of exoskeleton acceptance has not been investigated in depth within construction research. To objectively investigate the role of trialability in exoskeleton acceptance, it is critical to assess workers' perception towards the use of exoskeletons using a pre-and post-user evaluation approach supported by sound technology acceptance theories (Choi et al., 2017; Edirisinghe, 2019).

Understanding factors that influence individuals' use (acceptance) or rejection of a specific technology is a trending topic in marketing, information systems, construction management, and other social science domains (Tarhini et al., 2015); thus, researchers have developed theories and models to investigate, understand, predict and explain multiple variables that influence technology acceptance by workers and their respective construction organizations (Okpala et al. 2021). According to Venkatesh et al. (2003), these human behavior theories and methodologies have been satisfactorily used in the formulation of important and unique contributions to user acceptance of technology. In times past, a few of them have been conceptualized, synthesized, and tested to employ intention and/or usage as key dependent variables (in cross-sectional and between-subjects comparison). According to Tarhini et al. (2015), the key theories and models include the Theory of Reasoned Action (TRA), the Theory of Planned Behavior (TPB), the Technology Acceptance Model (TAM), and the extended TAM, the Unified Theory of Acceptance and Use of Technology (UTAUT), Innovation Resistance Theory and the Social Cognitive Theory. However, a recent study by Okpala et al. (2022b) indicates that UTAUT is the most effective model for explaining worker wearable device acceptance behavior within construction research. Given the lack of information on the role of trialability on WR acceptance, the present study aims to 1) identify factors/constructs that influence the acceptance of WR at the individual level in the construction industry, and 2) conduct a pilot study to assess the role of hands-on experience in behavior change using the constructs identified in the present study.

Background

Wearable Robots in Construction

Wearable robots, exoskeletons, exosuits, or super suits are a category of robotics and automation that comprises a system that produces a force or motion which augments the action of the wearer with increased strength and endurance during an activity (Fleischer & Hommel, 2008). The core benefit of a wearable robotic system is the enhanced ability of the construction worker to lift loads and engage in other manual handling activities with a lessened impact on body parts, such as their shoulders and lower backs (Zhu et al., 2021). This benefit is made possible by a combination of actuators, electrical systems, or/and hydraulics overlain by soft membranes or other suitable material in direct contact with the worker's skin (Kim et al., 2019). There are two broad classes of exoskeletons, namely active and passive exoskeletons. Active exoskeletons are those exosuits that use actuators in the form of electric motors, hydraulics, and pneumatics to provide support; while passive exoskeletons only use mechanical actuators like dampers and springs to store and release elastic energy as the worker engages in the movement of their body parts (Antwi-Afari et al., 2021). According to Exoskeleton Report (2022), examples of active exoskeletons are Iron Hand [upper body (wrist) type for grasping] and ATOUN Model Y (upper body type for bending and lifting). Passive exoskeletons include Ekso Vest (upper body type for elevated arm, static arm, and repeated arm motions), SuitX MAX (full body type for bending, lifting, squatting, elevated arms, and prolonged standing), and FLx ErgoSkeleton (upper body for pick and carry tasks).

Within the construction sector, studies on exoskeleton use have largely centered on experimental trials to demonstrate the efficacy in reducing physical demand on muscles associated with various body parts (Antwi-Afari et al., 2021, Gonsalves et al., 2021, Jain et al., 2021). Although Okpala et al. (2022a) deduced, through a survey of 51 construction and project managers, that wearable robotics could prevent between 30 and 40 % of injury incidents associated with critical WMSD risk factors, and can prevent construction-related WMSDs associated with all human body parts, there continues to be skepticism regarding their actual use on job sites (De Looze et al., 2016). Little to no research has focused on understanding the acceptance of exoskeletons before and after workers are exposed to the technology.

Role of User Experience in Technology Acceptance

When investigating technology acceptance, researchers have posited that the experience of the user (construction worker) is considered a technology-inherent determinant for raising technology acceptance (Mlekus et al., 2020; Vaziri et al., 2016). This supports the concept of trialability which connotes that the technology application functionality, after use, can influence how the worker's intention to adopt the device. In construction management and safety research, the exploration of predictive and explanatory theories/models have yielded results with a variety of degree of influences between independent and dependent variables (Choi et al., 2017; Lee et al., 2015; Okpala et al., 2022; Tarhini et al., 2015). In explaining or predicting technology acceptance in the construction domain, there is a lack of studies that experimentally assess the role of user experience. Just like in Rogers' diffusion theory of innovations (Sahn, 2006), Trialability (hands-on experience) could be critical to understanding how construction researchers should evaluate workers' behavior and attempt to influence adoption (Lee et al., 2011). In relating this position to the current research, it has been posited that trialability (when individuals use the exoskeleton for a task) can improve their views toward accepting the technology (Hayes et al., 2015). It is expected that information gotten from users before and after utilizing the exoskeletons will provide useful insights that support successful implementation within the construction domain.

Unified theory of acceptance and use of technology

The unified theory of acceptance and use of technology (UTAUT) is a more recent and comprehensive theory that has received significant attention in multiple research fields. As depicted in Figure 1, Lai (2017) explained that four constructs predict workers' behavioral intention to accept and use technology. The constructs are designated as (1) performance expectancy, (2) effort expectancy, (3) social influence, and (3) facilitating conditions.

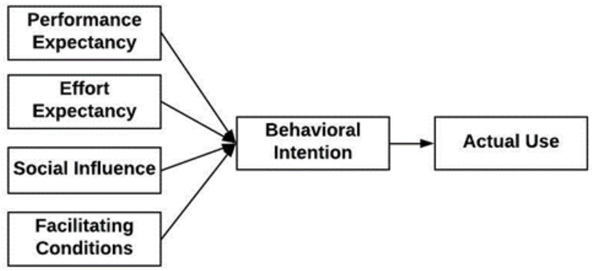

Figure 1. Unified Theory of Acceptance and Use of Technology (UTAUT)

According to Venkatesh et al. (2003), constructs such as perceived usefulness, extrinsic motivation, relative advantage, and outcome expectations form the performance expectancy in the UTAUT model while effort expectancy captures the notions of perceived ease of use and complexity. Herein, the facilitating conditions also correlate with the intention to use a technology, considering that they include factors highly reputed to make the action easy (Lee et al. 2011). Examples can be voluntariness of use, perceived behavioral control, and device wearability (Taherdoost 2018). These constructs could be used to assess workers' exoskeleton acceptance and provide a robust framework for assessing the impact of trialability on workers' acceptance. Table 1 summarizes questions (Items) used to assess each construct and relevant literature that supports each construct.

Table 1
Constructs and Items for UTAUT

Constructs	Items	References
Performance Expectancy (PE)	• Using Exoskeletons increases my productivity. • I think Exoskeletons help improve the quality of work. • Using Exoskeletons enhances my overall performance.	Rahman et al. (2017), Venkatesh et al. (2003)
Effort Expectancy (EE)	• Exoskeletons are very easy to operate. • Exoskeletons are easy to fit and adjust. • It is easy to learn how to use exoskeletons.	Rahman et al. (2017), Venkatesh et al., (2003), Zhang and Ng (2013)
Social Influence (SI)	• Using exoskeletons could make me look weak. • I have such an image that exoskeletons are difficult to use. • Exoskeletons are only useful for people who need help to finish a task.	Gledson, 2021; Kaur et al. (2020); Joachim et al., 2018
Facilitating Condition/ wearability (FC)	• The fit and overall comfort of exoskeletons are important for me. • I am reluctant to use exoskeletons that feel uncomfortable. • I am interested in using exoskeletons regardless of how I feel.	Bogue (2018); Sarac et al. (2019)
Behavioral Intention to Use (BI)	• I intend to use exoskeletons to perform drilling or similar tasks if given the opportunity. • I plan to continue using exoskeletons in the future. • All things considered, I will keep using exoskeletons as long as I have access to it.	Tarhini et al., (2015), Yousafzai et al. (2010), Choi et al. (2017)

Based on existing research, the research team hypothesizes that hands-on experience will significantly improve participants' perception of exoskeleton use.

Table 2
Research Hypotheses

ID	Hypothesis
H1 (PE)	Hands-on experience will significantly improve participants' perception of exoskeleton's perceived effectiveness.
H2 (PEU)	Hands-on experience will significantly improve participants' perception of exoskeleton's perceived ease of use.
H3 (SI)	Hands-on experience will significantly reduce participants' perception of the negative impression associated with the use of exoskeletons.
H4 (FC)	Hands-on experience using exoskeletons will significantly increase participants' perception of their wearability.
H3 (BI)	Hands-on experience will significantly increase participants' intention to use exoskeletons.

Research Methods

The present study implemented a three-phase research framework to achieve the research goal. This consists of the structured literature review and survey design; expert review of the survey questionnaire; and controlled experimentation. The literature review consisted of academic research articles pertinent to construction technology applications, and WRs in construction. This extensive search solely depended on generic platforms such as Web of Science, Scopus, and Google Scholar (Okpala et al., 2020). The literature review led to the identification of important technology acceptance models and theories. Following the selection of the applicable theories/models (UTAUT), the author developed a survey questionnaire using data from Table 1. The questionnaire was designed using a 5-point Likert scale which varied from 1= Strongly Disagree to 5= Strongly Agree. Three domain experts with an average of 10 years of experience in construction management and technology implementation reviewed the questionnaire items, thereby assessing the variables concerning WRs acceptance. Next, the research team utilized a within-subject simulation experiment to expose participants to exoskeletons. Twenty-five were recruited to participate in multiple simulated drilling tasks using exoskeletons over three sessions. These sessions typically lasted between 30 minutes to an hour, depending on the type of task and the number of rest participants needed. Each session was separated by at least 48 hours. Participants were asked to complete a questionnaire on acceptance before the first session and a few days after completing the last session.

A non-parametric repeated measure t-test was used to analyze responses received from participants since the data violated the equal variance and normality assumptions needed for parametric analysis. The Wilcoxon signed-rank test, which is an equivalent of the paired sample t-test, was used in the present study given that a pair of repeated measurements are assessed. The null hypotheses for these tests are presented in Table 1.

Results and Discussion

Out of the 25 participants, 18 (10 males, 8 female) healthy engineering students with no reported musculoskeletal issues or other related health that affects their ability to stand, walk, bend, and lift performed lab-simulated drilling tasks. Demographic statistics of participants as represented in mean were: age = 22 years; weight = 173 lbs.; and height = 5 feet and 8 inches. Table 3 shows the participants' ratings in response (median value) to the constructs influencing innovation acceptance and resistance before and after completing the drilling experiments using exoskeletons. The user perception of the participants on constructs that affect the acceptance of exoskeletons generally improved after they completed the experiments. However, some constructs remained the same which implies that using the exoskeletons to complete a task did not change their perception. Table 3 contains the results of the descriptive and inferential statistical analyses.

Table 3
Results of Descriptive and Inferential Statistical Analyses

Constructs	**Before Experiment**		**After Experiment**		**P-value**
	Median	**SD**	**Median**	**SD**	
Performance Expectancy (PE)	3.83	0.85	3.830	0.96	0.880
Perceived Effort Expectancy (PEE)	3.33	0.73	4.000	0.69	0.100
Social Influence (SI)	3.58	0.62	2.17	0.72	**0.000**
Facilitating Condition/Wearability (FC)	2.33	0.8	4.000	0.68	**0.000**
Behavioral Intention (BI)	3.67	0.81	4.000	0.71	0.600

H1: Performance expectancy (PE): Participants' perception of exoskeleton effectiveness did not change because of the experiment (median = 3.83, P-value = 0.88). This finding implies that using the exoskeletons to complete simulation tasks did not improve their perception of its effectiveness. It is important to note that the rating was above 3.0 which suggests that participants were positive about the technology's effectiveness.

H2: Perceived Effort Expectancy (PEE): After completing the tasks, the participants indicated an increase in the degree to which they believe that using the device will be free of effort (before = 3.33, after = 4.00, P-value = 0.10). Though this finding is not significant (P-value = 0.10), it illustrates the perceived non-complexity in handling the exoskeleton as opined by Choi et al. (2017).

H3: Social Influence (SI): As consistent with existing studies, the participants' SI reduced significantly after the experiment (before= 3.58, after = 2.17, P-value = 0.00) illustrating that using the technology demystified their perception towards potential social or image-related posed by the introduction of exoskeletons (Zhu et al., 2021). This result clearly shows that while end-users may have some concerns based on preconceived notions, timely exposure to exoskeletons will play a major role in revealing the true value of these technologies. Therefore, construction practitioners should consider implementing strategies that encourage the use of these technologies by workers in different work scenarios to improve their perceived behavioral control.

H4: Facilitating Conditions/Wearability (FC): The end-user perception of FC significantly improved (before = 2.33, after = 4.00, P-value = 0.00) after the experiment thus illustrating that the fit and overall comfort of the device is sufficient. This implies that while the participants had some concerns about wearability and fit prior to the experiments, these concerns reduced significantly after the experiment. It is important to note that the researchers worked closely with the participant to ensure proper fit before and during the experiments. The current design and information provided by the manufacturers were adequate and point to the need to ensure that safety managers and supervisors pay close attention to human-robot fit.

H5: Behavioral Intention (BI): The BI rating increased (before = 3.67, after = 4.00) after using the exoskeleton for the drilling task. Although the increase is not significant (P-value = 0.60), trialability could still play a role in increasing an end-users interest in using exoskeletons. It is important to note that the baseline BI was relatively high for the group evaluated in this study (Median score of 3.67 on a 5-point scale), thereby reducing the possibility of a significant difference post-hands-on experience. It is expected that hands-on experience will have a greater impact on participants with lower baseline BI, such as construction trade workers. This position is consistent with existing literature (Choi et al., 2017; Lee et al., 2015) and further demonstrates the effect of trialability on the perception of the participants.

Conclusion

Few studies have highlighted the benefits and barriers of using exoskeletons in the construction industry. Although these studies posit that WRs have a huge potential to reduce injuries, existing literature suggests that the use of WRs in the construction industry is relatively low. This has prompted a shift in orientation to focus on uncovering factors that influence individuals' use (acceptance) or rejection of the exoskeleton technology. More importantly, limited studies have evaluated the role of hands-on experience using objective and quantitative procedures. To fill this gap, the researcher utilized a mixed-method approach consisting of a structured literature review, a controlled experiment, and surveys (before and after the experiment). The study identified factors/constructs that influence the acceptance of WR at the individual level in the construction industry and assessed the role of hands-on experience on end-user acceptance behavior. Descriptive and inferential statistical analyses revealed that Trialability has a significant positive influence in 40% of the constructs assessed and a positive, but not significant impact on 40% of the constructs (including "Behavioral Intention to Use"). Therefore, the research team confirms that Trialability is an important component in exoskeleton integration research and practice. Given the results from the present pilot study, future studies should investigate the role of Trialability on trade workers' intention to use exoskeletons. The impact of age and experience should be assessed as well.

References

Antwi-Afari, M. F., Li, H., Anwer, S., Li, D., Yu, Y., Mi, H. Y., & Wuni, I. Y. (2021). Assessment of a passive exoskeleton system on spinal biomechanics and subjective responses during manual repetitive handling tasks among construction workers. *Safety Science*, 142, 105382.

Bock T. (2015) The future of construction automation: Technological disruption and the upcoming ubiquity of robotics. *Automation in Construction*. 59:113-21. https://doi.org/10.1016/j.autcon.2015.07.022

Bogue R. (2018) Exoskeletons–a review of industrial applications. *Industrial Robot: An International Journal.* https://doi.org/10.1108/IR-05-2018-0109

Choi, B., Hwang, S., & Lee, S. (2017). What drives construction workers' acceptance of wearable technologies in the workplace? indoor localization and wearable health devices for occupational safety and health. *Automation in Construction*, 84, 31-41. doi:10.1016/j.autcon.2017.08.005

De Looze, M. P., Bosch, T., Krause, F., Stadler, K. S., & O'sullivan, L. W. (2016). Exoskeletons for industrial application and their potential effects on physical workload. *Ergonomics*, 59(5), 671-681.

Delgado, J. M, Oyedele, L., Ajayi, A., Akanbi, L., Akinade, O., Bilal, M., & Owolabi, H.. (2019). Robotics and automated systems in construction: Understanding industry-specific challenges for adoption. *Journal of Building Engineering*. 1;26:100868. https://doi.org/10.1016/j.jobe.2019.100868

Exoskeleton Report (2022) Exoskeleton Catalog. Retrieved from: <https://exoskeletonreport.com/product-category/exoskeleton-catalog/> (January 14, 2022)

Fleischer, C., a& Hommel, G. (2008). A human--exoskeleton interface utilizing electromyography. *IEEE Transactions on Robotics*, 24(4), 872-882.

Galin, R. R., & Meshcheryakov, R. V. (2020). Human-robot interaction efficiency and human-robot collaboration. *In Robotics: Industry 4.0 Issues and New Intelligent Control Paradigms* (pp. 55-63). Springer, Cham.

Gledson, B. (2021). An enhanced model of the innovation-decision process, for modular-technological-process innovations in construction. *Construction Innovation*.

Gonsalves, N. J., Ogunseiju, O. R., Akanmu, A. A., & Nnaji, C. A. (2021). Assessment of a passive wearable robot for reducing low back disorders during rebar work. *Journal of Information Technology in Construction (ITCON)*, 26, 936-952.

Hayes, K. J., Eljiz, K., Dadich, A., Fitzgerald, J. A., & Sloan, T. (2015). Trialability, observability, and risk reduction accelerate individual innovation adoption decisions". *Journal of health organization and management.*

Harty, C. (2008). Implementing innovation in construction: contexts, relative boundedness and actor-network theory. *Construction management and economics*, 26(10), 1029-1041.

Joachim, V., Spieth, P., & Heidenreich, S. (2018). Active innovation resistance: An empirical study on functional and psychological barriers to innovation adoption in different contexts. *Industrial Marketing Management*, 71, 95-107.

Kaur, P., Dhir, A., Singh, N., Sahu, G., & Almotairi, M. (2020). An innovation resistance theory perspective on mobile payment solutions. *Journal of Retailing and Consumer Services*, 55, 102059.

Kermavnar, T., de Vries, A. W., de Looze, M. P., & O'Sullivan, L. W. (2021). Effects of industrial back-support exoskeletons on body loading and user experience: an updated systematic review. *Ergonomics*, 64(6), 685-711.

Kim, S., Moore, A., Srinivasan, D., Akanmu, A., Barr, A., Harris-Adamson, C., ... & Nussbaum, M. A. (2019). Potential of exoskeleton technologies to enhance safety, health, and performance in construction: Industry perspectives and future research directions. *IISE Transactions on Occupational Ergonomics and Human Factors*, *7*(3-4), 185-191.

Lee, Y. H., Hsieh, Y. C., & Hsu, C. N. (2011). Adding innovation diffusion theory to the technology acceptance model: Supporting employees' intentions to use e-learning systems. *Journal of Educational Technology and Society,* 14(4), 124-137.

Lee, S., Yu, J., & Jeong, D. (2015). BIM acceptance model in construction organizations. *Journal of management in engineering*, 31(3), 04014048.

Mlekus, L., Bentler, D., Paruzel, A., Kato-Beiderwieden, A. L., &and Maier, G. W. (2020). How to raise technology acceptance: user experience characteristics as technology-inherent determinants. *Gruppe. Interaktion. Organisation. Zeitschrift für Angewandte Organisationspsychologie (GIO),* 51(3), 273-283.

Nnaji, C., & Karakhan, A. A. (2020). Technologies for safety and health management in construction: Current use, implementation benefits and limitations, and adoption barriers. *Journal of Building Engineering*, 29, 101212.

Okpala, I., Nnaji, C., Awolusi, I., & Akanmu, A. (2021). Developing a success model for assessing the impact of wearable sensing devices in the construction industry. *Journal of Construction Engineering and Management*, *147*(7), 04021060.

Okpala, I., Nnaji, C., & Karakhan, A. A. (2020) Utilizing emerging technologies for construction safety risk mitigation. *Practice Periodical on Structural Design and Construction*. 25(2):04020002. https://doi.org/10.1061/(ASCE)SC.1943-5576.0000468

Okpala I., Nnaji C., Ogunseiju O., & Akanmu A. (2022a) Assessing the role of wearable robotics in the construction industry: potential safety benefits, opportunities, and implementation barriers.

Automation and Robotics in the Architecture, Engineering, and Construction Industry. Springer, Cham. https://doi.org/10.1007/978-3-030-77163-8_8

Okpala, I., Nnaji, C., & Awolusi, I. (2022b). Wearable sensing devices acceptance behavior in construction safety and health: assessing existing models and developing a hybrid conceptual model. *Construction Innovation*, *22*(1), 57-75.

Rahman, M. M., Lesch, M. F., Horrey, W. J., & Strawderman, L. (2017). Assessing the utility of TAM, TPB, and UTAUT for advanced driver assistance systems. *Accident Analysis and Prevention,* 108, 361-373

Sahin, I. (2006). Detailed review of Rogers' diffusion of innovations theory and educational technology-related studies based on Rogers' theory. *Turkish Online Journal of Educational Technology-TOJET*, 5(2), 14-23.

Sarac, M., Solazzi, M., & Frisoli, A. (2019). Design requirements of generic hand exoskeletons and survey of hand exoskeletons for rehabilitation, assistive, or haptic use. *IEEE transactions on haptics*, 12(4), 400-413.

Shore, L., Power, V., De Eyto, A., & O'Sullivan, L. W. (2018). Technology acceptance and user-centred design of assistive exoskeletons for older adults: A commentary. Robotics, 7(1), 3.

SmartMarket Report. (2021). Safety management in the construction industry 2021. *Bedford, MA: Dodge Data and Analytics*

Tarhini, A., Arachchilage, N. A. G., & Abbasi, M. S. (2015), A critical review of theories and models of technology adoption and acceptance in information system research. *International Journal of Technology Diffusion (IJTD),* 6(4), 58-77.

Vaziri, D.D., Aal, K., Ogonowski, C., Von Rekowski, T., Kroll, M., Marston, H.R., Poveda, R., Gschwind, Y.J., Delbaere, K., Wieching, R. & Wulf, V. (2016). Exploring user experience and technology acceptance for a fall prevention system: results from a randomized clinical trial and a living lab. *European Review of Aging and Physical Activity*, 13(1), pp.1-9.

Venkatesh, V., Morris, M. G., Davis, G. B., & Davis, F. D. (2003). User acceptance of information technology: Toward a unified view. *MIS Quarterly*, 425-478.

Venkatesh, V., Thong, J. Y., Chan, F. K., Hu, P. J. H., & Brown, S. A. (2011). Extending the two-stage information systems continuance model: Incorporating UTAUT predictors and the role of context. *Information Systems Journal*, 21(6), 527-555.

Yousafzai, S. Y., Foxall, G. R., & Pallister, J. G. (2010), Explaining internet banking behavior: theory of reasoned action, theory of planned behavior, or technology acceptance model? *Journal of applied social psychology*, 40(5), 1172-1202.

Zhang, P., & Ng, F. F. (2013), Explaining knowledge-sharing intention in construction teams in Hong Kong. *Journal of Construction Engineering and Management*, 139(3), 280-293.

Zhu, Z., Dutta, A., & Dai, F. (2021). Exoskeletons for manual material handling–A review and implication for construction applications. *Automation in Construction*, 122, 103493.

State of Construction Spanish and Hispanic Safety Culture Education in the US

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According to research studies, Hispanic and Spanish speaking labors make up about 30% of the fatalities in the construction industry. Experts concur that the language barrier between Spanish-speaking workers and English-speaking supervisors is the primary reason for these high rates. Construction Spanish courses need to be taught in construction management departments in colleges throughout the US in order to reduce the language/communication gap between labors and future construction managers or superintendents. This study examines the construction Spanish and Hispanic safety culture courses that are taught in construction programs in the US. It was determined that only a few construction Spanish courses are taught. There is a need to teach students construction Spanish language and Hispanic safety culture in order to reduce the rate of the Hispanic workforce fatalities and injuries.

Key Words: Construction Spanish, Hispanic Safety Culture, Phrases, Study Abroad

Introduction

In the U.S. construction industry, where a skilled labor shortage is a continuing problem, Hispanics represent a significant portion of the labor force. One in three workers in the US construction industry is Hispanic. The US Bureau of Labor Statistics (Na, 2022) reports that nearly one-third (31.5%) of the construction labor force is made up of Hispanics; additionally, the most common foreign language spoken among construction workers is Spanish at 75.2%. The US Hispanic labor force participation increased from 10.7 million in 1990 to 29.0 million in 2020 and is anticipated to reach 35.9 million in 2030 according to a US department of Labor blog (Dubina, 2021).

The most important demographic on the Hispanic workforce is job safety. The US Bureau of Labor Statistics (Na, 2022) reports that the Hispanic and Latino worker deaths as a percentage of total workforce have been increasing every year since 2011.

The literature shows that the majority of the Hispanic work-related fatalities and injuries can be attributed to their safety culture and communication barriers. Lavy and Porwal (2010) examined the safety measures taken by construction companies to address the linguistic and cultural barriers that exist among their Hispanic workforces. They concluded that the growing frequency of fatalities among Hispanic workers in the construction sector indicates that not enough is being done to address the linguistic and cultural issues these workers' encounter.

Mowery (2017) surveyed construction industry executives, vice presidents, project managers, superintendents, assistant project managers, assistant superintendents, and field project engineers to identify the leading problems that English-Spanish language barrier creates in the industry. The results showed that 95.4% of the respondents indicated that a language barrier exists, with 65% of the respondents indicating that the problem is worsening over time. The study also showed that the top four consequences due to this language barrier were (1) difficulty in giving instructions (basic jobsite communication) at 30%, (2) greater safety risk at 27.3%, (3) loss of productivity/efficiency at 22.4%, and (4) lack of respect/diminished team atmosphere at 17.9%.

Mowery's (2017) research survey also showed that some construction companies are taking steps to teach Spanish to their English-speaking employees. These steps include training sessions; providing Spanish tutors, reference manuals/handbooks, and pocket translators; and hiring bilingual employees to mentor or teach. The survey participants responded that it is more likely and assumed more beneficial to teach Spanish to English-speaking individuals since their top consequence due to the language barrier was difficulty in giving instructions (basic jobsite communication).
These findings beg the question, how many construction programs across the country teach construction Spanish and/or Hispanic safety culture? The purpose of this study is to ascertain the state of construction Spanish and Hispanic safety culture education among the Associated Schools of Construction (ASC) in the US. Are ASC member schools doing their part to teach students construction Spanish and Hispanic safety culture in order to close the gap on the language/communication and cultural safety barriers that exists on construction jobsites among the English-speaking supervisors and Spanish-speaking workers?

Literature Review

The literature search showed that some effort has been made to develop college level courses on the topic of construction Spanish and Hispanic safety culture. Lopez del Puerto (2009) performed a comparative analysis on the "results between two Spanish for Construction class formats: a three credit (45 contact hours) junior/senior-level undergraduate course offered at Southern Illinois University- Edwardsville in Spring 2008 and a 16-contact hour module in a junior-level undergraduate internship at The University of Oklahoma also offered in Spring 2008. The course goal was to teach job-specific Spanish to non-Spanish speaking construction management personnel, with the long-term goal of improving job-site safety." In a paper titled, "Relevant, Memorable, and Brief: A New Approach to Teaching Spanish in a Construction Safety Course," Jenkins and Hartmann (2016) discussed the addition of construction Spanish to a safety course at Purdue University. Both the 2009 and the 2016 studies recommended that construction Spanish should be taught to construction management students.

Methodology

A qualitative cross-sectional research method was used to conduct this study. The detailed research methodology in outlined in Figure 1.

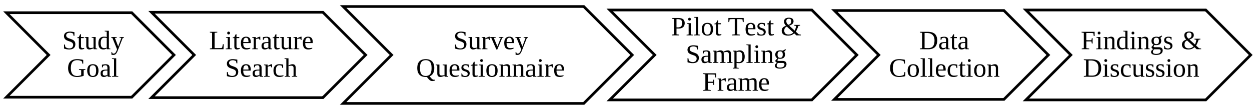

Figure 1. Methodology

Study Goal and Literature Search

The goal of this study was to determine the state of construction Spanish and Hispanic safety culture education among the Associated Schools of Construction (ASC) in the US. The aim of this study is to address the research question, are ASC member schools teaching students construction Spanish and Hispanic safety culture in order to close the gap on the language/communication and cultural safety barriers that exists on construction jobsites among the English-speaking supervisors and Spanish-speaking workers?

The first step in this study was to conduct a literature search to determine what has been published on the subject of construction Spanish and/or Hispanic safety culture college level courses.
The second step in this study was to develop a survey questionnaire to determine if construction Spanish and Hispanic safety culture are offered at ASC member schools.

The third step in this study was to pilot test the survey questionnaire and then send out it to the ASC member school department chairs and coordinators throughout the US.

The fourth step in this study was to compile the survey responses and discuss the findings.
The fifth step in the study was to draw conclusions and make recommendations.

Survey Questionnaire, Pilot Test, Sampling Frame, and Data Collection

As a result of the limited published literature on construction Spanish and Hispanic safety culture taught at the college level, a survey questionnaire was developed to determine if construction Spanish and Hispanic safety culture are being taught at ASC member schools and to what extent. The survey instrument was pilot tested. The sampling frame for this study was the member schools of ASC. Qualtrics, a web-based system, was used for data collection. The survey questions included background information: university name and name of department/program. The next four questions inquired if they offered a standalone construction Spanish course: are standalone construction Spanish course(s) taught in your program? If yes, what is the course(s) name, number, and number of credit hours? Is the course a required or an elective course? How often is the course offered?

The next four questions inquired about the program’s option if a standalone course was not offered: is Spanish taught as part of another course? If yes, what is the course number, name, and number of credit hours? If no, do you require students to take a Spanish course from another department? If yes, which course?

The next four question inquired if they offered a standalone course on Hispanic safety culture: do you have a standalone course on Hispanic safety culture? If yes, what is the course(s) name, number, and number of credit hours? Is the course a required or an elective course? How often is the course offered?

The next two questions inquired about the program's option if a standalone course was not offered: do you require students to take a course on Hispanic culture from another department? If yes, which course?

The last two questions inquired about a study abroad course to a Spanish-speaking country: do you have a study abroad course to a Spanish-speaking country? The response choices were: Yes, traveling to a country for an entire semester/quarter/mini-semester; Yes, traveling to a country for part of the semester/quarter; Yes, no travel-it's virtual; No. If yes, what is the course(s) name, number, and number of credit hours? And which country? How often is the course offered?

Findings and Discussion

The survey was emailed to 97 programs across the country. There were 14 responses, a response rate of 14.4%. The response to each question is discussed below.

The response to the question, "Name of your Program or Department": Out of 14 responses that were received, 5 were from construction management program and the remaining were from construction building/engineering/technology/science program.

The response to the question, "Are standalone Construction Spanish course(s) taught in your program?": out of the 14 responses that were received, 13 said No and 1 said Yes. That is 92.9% of the respondents do not have a standalone construction Spanish course offered at their program. Only one (7.1%) said that they have a standalone course construction Spanish course taught in their program. The course is called Technical Construction Spanish for the Jobsite, a 3 credit-hour required course taught every semester. For the 13 that said no, construction Spanish is not taught as part of another course in their program, nor do they require their students to take Spanish from another department.

When asked if there are any standalone courses on Hispanic Safety Culture that are taught in their program, all 14 (100%) respondents said no, nor do they require their students to take a course on Hispanic culture from another department.

When asked about if their department offers a study abroad course to a Spanish speaking country, 13 out of the 14 respondents said no. One said yes, traveling to Costa Rica for part of a semester. The course is a 3 credit-hour course offered in the Spring semester.

Conclusion

There is a vast volume of research which shows that the majority of the Hispanic work-related fatalities and injuries can be attributed to their safety culture and language/communication barriers. Mowery's (2017) survey of construction industry executives, vice presidents, project managers, superintendents, assistant project managers, assistant superintendents, and field project engineers believe that English-Spanish language barrier exists and that the impact of the problem is worsening over time because of the increase in the Hispanic workforce on construction jobsites. This same group stated that the top four consequences due to this language barrier are (1) difficulty in giving instructions (basic jobsite communication), (2) greater safety risk, (3) loss of productivity/efficiency, and (4) lack of respect/diminished team atmosphere. They also believe that it is more beneficial to teach Spanish to English-speaking individuals since their top consequence due to the language barrier is difficulty in giving instructions (basic jobsite communication).

The idea of breaking down the communication barrier between English-speaking supervisors and Spanish-speaking workers by teaching future construction managers essential construction Spanish terms and phrases is not a novel one. A few courses in construction Spanish are provided by a select few institutions and universities. This research demonstrates additional evidence that there are a very limited construction Spanish and Hispanic safety related courses being taught at construction management programs across the US. It is imperative to teach construction Spanish and Hispanic safety culture to students in construction related fields to better prepare them for the challenges they will face in practice and to reduce the Hispanic workforce rate of injuries and fatalities on construction jobsites.

For future study, a list of commonly spoken English phrases by construction jobsite field supervision needs to be developed. These phrases will then need to be translated and transliterated into Mexican and Central American Spanish since majority of the Hispanic construction workforce comes from Mexico and Central America. These phrases can then be taught to students in construction related programs through a course developed to teach construction Spanish and Hispanic safety culture. Study abroad courses to Spanish-speaking countries will provide first-hand experience into understanding the Hispanic safety culture.

References

Dubina, K. (Sept 15,2021). US Department of Labor Blog, https://blog.dol.gov/2021/09/15/hispanics-in-the-labor-force-5-facts#:~:text=29%20million,reach%2035.9%20million%20in%202030.

Jenkins, J. and Hartmann, B. (2016). *Relevant, Memorable, and Brief: A new Approach to Teaching Spanish in a Construction Safety Course*, International Proceedings of Associated Schools of Construction, 52nd Annual Conference, Provo, UT

Levy, S. and Porwal, V. (2010), *Fatalities of Hispanic Workers: Safety Initiatives Taken by U.S. Construction Companies to Address Linguistic and Cultural Issues*, https://www.researchgate.net/publication/232901446_Fatalities_of_Hispanic_Workers_Safety_Initiatives_Taken_by_US_Construction_Companies_to_Address_Linguistic_and_Cultural_Issues

Lopez del Puerto, C. (2009). *Comparative Analysis of Construction Spanish Class Format Results*, International Proceedings of Associated Schools of Construction, 45th Annual Conference, Gainesville, FL

Mowery, C. (2017). *Consequences of the English-Spanish Language Barrier in the Construction Industry*, https://www.engr.psu.edu/ae/thesis/portfolios/2008/cam459/SPRING/Posting/Mowery_Casey_9-Analysis%201_Consequences%20of%20the%20English-Spanish%20Language%20Barrier.pdf

Na, Z. (June 23, 2022). *One in three workers isHispanic*, https://eyeonhousing.org/2022/06/one-in-three-workers-in-construction-is-hispanic/#:~:text=Hispanics%20are%20overrepresented%20in%20the,underrepresented%20in%20the%20construction%20industry.

Theoretical Models for Evaluating and Predicting the Diffusion of Safety Technologies in Construction

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Several studies have investigated the benefits of applying emerging technologies in the construction industry, but information about how these technologies can be successfully implemented in construction, particularly for safety management is limited. Different theories and frameworks have been posited and successfully implemented in different industries. However, a detailed exploration of the utility of these frameworks within the context of construction safety management is missing. The main purpose of this research is to synthesize available information on different applicable theoretical models for evaluating and predicting the diffusion of safety technologies in construction. Using an integrated review process, the authors evaluated 12 promising theories and models that are rarely utilized in construction research. Potential applications, strengths, and limitations are discussed herein. The results of the review are used to propose multiple theoretical models that could be utilized to better understand and predict the diffusion of safety technologies in the construction industry. This study reveals the key factors, within multiple frameworks, that affect the adoption, adaptation, and infusion of technologies for safety management in construction. Practitioners and researchers could utilize information from this study to evaluate the diffusion of specific technologies within an organization and the construction industry.

Keywords: Construction Safety, Decision Support, Diffusion, Explanatory Model, Predictive Model, Safety Technology, Theoretical Model.

Introduction

The construction industry is known to be highly fragmented with the work environment characterized by different levels of operations within the project, organization, and across the industry (Hu et al., 2019). Although the use of technologies in the construction industry has shown some potential to improve work performance, research studies suggest that the industry still suffers pushback from employees (Wang et al., 2020). Hence, the examination of end-user behavior, and the use and impact of technologies to encourage extended use is very crucial before deciding to invest significantly in a technology (Jin et al. 2019). The quest to salvage this situation has prompted researchers to continuously investigate factors critical to successful technology integration (Darko et al., 2017) using explanatory and predictive theories and models which have proven to be effective in information systems research (Chin et al., 2020; Tarhini et al., 2015; Taherdoost, 2018; Okpala et al., 2022). To provide research direction into the technology adoption process and potential research areas, Sepasgozar et al. (2016)

reviewed construction technology adoption in the construction industry, with an emphasis on equipment utility and information flow. Like Sepasgozar et al. (2021), the proposed conceptual models developed centered on the adoption of subprocesses and modeling-specific technologies (mixed reality and digital twin). These models allow for (1) explanatory modeling, the establishment of causal relationships between technology acceptance/use and factors attributed to individual workers, technologies, and environmental factors, and (2) predictive modeling which is the determination of the combination of adoption factors that best predict technology use (Sainani, 2014).

Although construction researchers have been utilizing these theories and models to gain insight into factors that explain and predict different types of technologies used within the sector, there is no domain-specific synthesis on how these theories and models can be used as tools to facilitate the integration of emerging construction technologies. Conversely, other sectors, such as healthcare (Omachonu & Einspruch, 2010) and manufacturing (Taherdoost, 2018), have conducted several syntheses on these theories and models, and have developed contextual insight geared toward guiding future research and development. Therefore, this paper synthesizes available information on different applicable theoretical models for evaluating and predicting the diffusion of technologies for safety and health management in construction.

Literature Review

Technological Innovation and Use in Construction

The project-based nature, constant need for collaboration, inter-organizational activities, power distribution in practice, and established avenues for communication and data sharing (Harty, 2008) make the construction industry is unique and complex sector. Although these special attributes have made innovation and other industry transformations an uphill task (Green, 2011), researchers and practitioners have continued to pursue the development and implementation of technological solutions to continuously enhance work output (Sherratt et al., 2020). The level of saturation attained in the use of traditional work programs to improve key project success factors also makes a strong case for the need to increase technological innovation research and application in construction (Esmaeili & Hallowell, 2012). When compared to other industries, innovation integration and productivity rates within construction are relatively low (Ozorhon, 2013) thus, emphasizing the need for more research studies in this area (Liu & Liu, 2017).

A number of studies have discussed technology applications in different areas of construction management including safety and health management (Okpala et al., 2020), performance and productivity (Kim et al., 2019), cost (Martínez-Rojas et al., 2016), schedule (Uusitalo et al., 2017), and quality (El-Omari & Moselhi, 2011; Ogunrinde et al., 2020). The different categories of technologies discussed in these studies include enhanced information technologies, geospatial technologies, imaging technologies (photogrammetry and laser scanning), immersive visualization technologies (Building information modeling, augmented reality, and virtual reality), robotics and automation, and wearable technologies (Awolusi et al., 2018; Choi et al., 2017; Shen et al., 2017). Despite the potential of these technologies to positively impact workers and project performance within construction, their integration and diffusion still fall behind (Chen et al., 2020). To enhance the technology integration process (TIP) for existing and emerging technologies, a proper understanding of phases is essential to the successful integration of innovation into a new environment.

Technology adoption and integration occur at four levels – individual, project, organization, and industry level. In holistically assessing the status quo in technology integration, researchers have explored innovation frameworks incorporating industry-specific drivers, enablers, and barriers to innovation integration industry-wide (Owolabi et al., 2019), organizational/firm-level (Slaughter, 2000), project level (Ozorhon et al., 2016), and the individual level (Choi et al., 2017). To successfully integrate technology in the construction sector, there is a need for a hybrid (top-down and bottom-up) adoption approach that accounts for factors (drivers, barriers, and enablers) impacting all levels (Nnaji et al., 2019). Predictive and explanatory models rely on these factors to deliver realistic and significant contextual information on potential adoption and acceptance.

Predictive and Explanatory Technology Integration Modeling

Technology integration models and theories are analyzed and operationalized using predictive and explanatory modeling processes (Shmueli & Koppius, 2011). Valuable outputs have been reported within the past decades about the prediction and explanation of factors that impact technology adoption at different levels in the construction domain (Tarhini et al., 2015). Explanatory modeling is focused on evaluating the causal relationships between constructs (portraying individuals, a project, or an organization), while predictive modeling deals with the forecasting of an end construct made possible by a combination of independent adoption factors (Sainani, 2014). In order to correctly explain technology acceptance (behavioral intention or actual use) using independent variables (causal influences), the prediction must be accurate (Abbasi et al., 2015) because inaccurate predictions could lead to suspect decision-making, resulting in a failed TIP. Within the last four decades, researchers in the information systems research domain have developed multiple models and theories for explaining and predicting user adoption and acceptance (Davis, 1989). At the individual level, researchers have repeatedly and satisfactorily used the Technology Acceptance Model (TAM) (Davis, 1989; Davis et al., 1989; Lee et al., 2015), the Theory of Planned Behaviour (TPB) (Ajzen, 1991; Liu, 2020), and the Unified Theory of Acceptance and Use of Technology (UTAUT) (Okpala et al., 2022; Williams et al., 2015; Venkatesh et al., 2003) in modeling technology and system-based acceptance using a variety of technology attributes and contextual factors (Rahman et al., 2017).

The TAM is made up of key acceptance constructs: Perceived Usefulness (PU), Perceived Ease of Use (PEU), Attitude (ATT), Behavioural Intention to Use (BI), and Actual Use (Davis et al., 1989), with behavioral intention being the measure of actual technology use (Davis et al., 1989). The UTAUT incorporates “facilitating conditions,” a new construct which when with the other four constructs, Performance Expectancy (PE), Behaviour and Actual Behaviour (Actual Use), Effort Expectancy (EE), and Social Influence (SI) (Venkatesh et al., 2003), capture workers’ perception of availability of internal and external resources necessary for using a new technology (Tao et al., 2020). Other existing predictive and explanatory models which can be utilized in construction include the Theory of Reasoned Action (TRA), the extended TAM (TAM2), the Task-technology fit model, the Motivational Model, the Diffusion of Innovation Theory, PESTEL analysis, the Technology-Organization-Environment model, Explanation-confirmation Model, change and knowledge management theory, MITE (management, individual, technology, and environment), and Social Cognitive (Tarhini et al., 2015).

Research Method

This study presents an integrated review of the use of predictive and explanatory models in construction technology integration research. A mainstream paper database, Scopus, was utilized (Ayodele et al., 2020) to source relevant publications. These databases have the reputation of housing comprehensive information (title, abstract, citation, and keywords) of articles directly sourced from major building, construction, innovation, and project management journals (Hu et al., 2019). The authors searched for articles within Scopus using relevant keywords/keyphrases appropriately combined. The keywords included Construction AND (technology acceptance OR technology adoption OR model OR theory OR path analysis OR structural equation modeling OR regression OR project OR organization OR industry OR explanatory modeling OR predictive modeling OR construction management OR variables OR constructs OR confirmatory factor analysis OR regression analysis). The initial database search yielded 233 articles. In selecting and filtering the identified publications, the authors utilized several important criteria such as publication basic information, subject areas, etc., to assess the research papers for eligibility (Hu et al., 2019). A total of 109 articles were included for quality assessment and 35 out of those were included in this review, thus excluding 74 papers that did not meet the established criteria for this study.

The content of selected articles was analyzed in detail to 1) establish a description of the articles alongside their journal sources, publication year, and the spread by articles' country of origin; 2) trend different methods and theories used for predicting technology adoption and acceptance, and; 3) develop insight to guide the quality of future studies on forecasting technological applications in construction. Content analysis, as a research technique, has been utilized in multiple fields, and for determining major themes, trends, and other qualitative and quantitative metrics derived from messages (written, verbal, or visual), and depending on the project research problem to be solved (Siraj & Fayek, 2019).

Findings and Discussion

Predicting Technology Adoption and Acceptance in Construction

An evaluation of the existing theories and models utilized in construction technology integration research shows that TAM stands out as the primary basis for explaining acceptance and predicting acceptance. A visible trend exists in which researchers move to optimize the base models to ensure that the measurement model closely represents real-life construction situations (Lee et al. 2015). For example, Choi et al. (2017) introduced the “Perceived Privacy Risk” construct to evaluate workers’ concerns regarding the handling of personal information in the use of wearable technologies. Table 1 presents a summary of information (e.g., technology investigated, countries, and the primary application of the models) from some independent studies about acceptance theories and models in construction technology research.

As seen in Table 1, Building Information Modelling (BIM) stands out as the technology commonly investigated, followed by wearable technologies (WT), enterprise resource planning (ERP) systems, augmented reality (AR), and other smart construction systems (SCS) such as robotics and mobile computing (MC). Others investigated include information and communications technology (ICT), online project information management system (OPIMS), remotely piloted aircraft (RPA), Building Management Systems (BMS), Web-based Training (WBT), and prefabrication. This could be attributed to the high industry acceptance level of BIM when compared to other technologies or systems (Son et al., 2012), hence, the need to further investigate workers’ perceptions from different schools of thought. Most studies sampled construction practitioners and utilized data obtained to test measurement models and obtain insights critical to understanding the behavioral intention to use a technology, and actual use (Lee & Yu, 2017). In addition, when closely looking at the primary applications of the technology, there is a healthy mix between the individual, project, organization, and industry-level scenarios. The choice of which level of application is largely dependent on the researchers’ project direction hence, currently, the authors found some precursors for the future choice of technological primary application focus. It is necessary to state that a number of existing technologies tested as presented in the Table (BIM, ICT tools, MC; RPA) are well past the development stage (Chen et al., 2020; Choi et al., 2017) and have begun to find increased construction use. This explains the absence of technologies like artificial intelligence, wearable robotics, single-task construction robots, and other emerging technologies that are still being developed and optimized for productive construction use.

Table 1
Acceptance Theories and Models in Construction Technology Research

Theory/Model	Technology	Country	Application
TAM	BIM, WT, SCS, OPIMS, ICT, AR, ERP, BMS, Prefab, ICA	South Korea, USA, China, Ghana, Australia, Peru, Malaysia, United Kingdom, Norway, Netherlands	Individual, Projects, Organization, Industry.
TAM2	WBT, WT, BIM, ICT, ERP, SCS	South Korea, USA,	Individual, Project, Organization, Industry.
TAM3	BIM	South Korea	Organization
D&M model	WT, BIM, ERP	USA, South Korea	Project, Organization, Industry
TPB	WT, BIM, ICT	USA, South Korea, Netherlands	Organization, Industry
IDT	BIM	South Korea, China	Project, Industry
UTAUT	WT, BIM, ICT	USA, South Korea, United Kingdom, Peru, Netherlands, Australia	Individual, Project, Organization, Industry
Equity Theory	BIM	China	Project
ECM	BIM	China	Individual
TTF	BIM, RPA	South Korea, Australia	Project, Organization
DOI	OPIMS	Australia	Industry

Constructs Influencing Construction Technology Acceptance Decisions

The findings of the review process show that the Technology Acceptance Model (TAM), extended-TAM, UTAUT, Diffusion of Innovation Theory (IDT), Expectation-confirmation model (ECM), Task Technology Fit (TTF), and the DeLone and McLean IS Success Model have been utilized as a stand-alone model, in combination with other models, or as a fundamental framework for the conceptualization of novel models to explain or predict technology acceptance. The critical constructs and their respective models which commonly contain the constructs are shown in Table 2. The data presented in Table 2 highlight key constructs that construction researchers believe impact technology acceptance decisions indicating that these constructs will most likely be commonly used in future studies. For instance, it could be very critical to test if or not individual users think a new technology is useful (perceived usefulness) and easily operatable (perceived ease of use). Moreover, if workers think the work environment (facilitating conditions) enables them to productively use the new technology, additional critical insights on whether they intend to use the technology (Behavioural Intention) or to continue using the technology (Actual Use) may need to be generated. From the studies accessed, commonly considered moderators include gender, age, experience, project size, and project type (Wang et al. 2020; Aroke et al., 2022). The authors believe that researchers and practitioners must understand intrinsic population characteristics which can affect the outcomes of quantitative analyses aimed at predicting technology integration.

The performance of models was also evaluated to determine which models currently stand out as high-performing models in terms of ability to explain total variance or predictive power. The results indicate that the Technology Acceptance Model and the Unified Theory of Acceptance and Use of Technology (UTAUT) outperform other models and theories in terms of the predictive power of the behavioral intention to use a new technology. The weaker models identified in the present study are conceptual hybrid models that incorporate TAM and other theories such as Innovation Diffusion and Equity Theories.

Table 2
Constructs Influencing Construction Technology Acceptance Decisions

Constructs	Definition	Theory/Model
Perceived Usefulness (PU); Performance Expectancy (PE)	The extent of individual belief regarding how the use of a particular technology will enhance work performance.	TAM, TPB, TAM2, UTAUT
Perceived Ease of Use (PEU); Effort Expectancy (EE)	The extent of individual belief regarding how the use of a particular technology would be free of effort.	TAM, TAM2, UTAUT
Subjective Norm (SN); Social Influence (SI)	The extent to which an individual thinks that it is vital that others should utilize the new technology.	TPB, TAM2, UTAUT
Behavioral Intention (BI)	An estimate of the strength of an individual's intention to act in a specified way.	TAM, TPB, TAM2, UTAUT
Actual usage Behavior (AU)	The actual behavior of people using a system.	TAM, TPB, TAM2, UTAUT
Attitude (ATT)	An individual's specific beliefs and degree of emotional attraction toward a system.	TAM, TPB
Perceived Behavioural Control (PBC)	The perceived ease or difficulty of an individual acting in a specified way.	TPB
Facilitating Conditions (FC)	Environmental factors designed to make an act easy to be carried out.	UTAUT

Conclusion and Further Research

Technology acceptance theories and models are under-researched in the construction domain compared to other sectors like health, information systems, education, and manufacturing. However, few studies on technology acceptance have been performed across the globe and published in top journals with only a few technologies and application schemes being sufficiently explored. There is a need for a more comprehensive reach and the influx of systematic studies that could be assisted by insights developed in the present study. To facilitate construction technology adoption, it is imperative that researchers keep exploring the use of technology integration modeling at all levels (individual, project, organizational, and industry levels) and across different integration phases. For some studies, the model could contain different sub-domain characteristics. These explanatory and predictive models and theories can find very productive applications as decision-support tools in construction organizations ready to explore and possibly adopt novel work strategies and technological advancement. It is also important to preserve and continue seeking ways to improve upon existing quantitative predictive and explorative modeling methods.

Technology integration has become pertinent in the push for significant improvements in the construction sector in terms of productivity, safety, cost and schedule, and quality. To achieve this improvement, there is a pressing need for construction researchers and practitioners to work towards the development, optimization, and usage of empirical tools to foster the effective integration of technologies into construction operations. This effort requires a proper understanding of factors that influence the behavioral intention to the use, and actual usage of construction technologies. Using a systematic review, this study has summarized the current state of development and usage of explanatory and predictive tools to forecast technology acceptance. This study contributes to knowledge and practice in construction by 1) systematically reviewing the body of knowledge about the models and theories used for technology integration research in construction thus, providing critical case studies for practitioners, and laying a solid foundation for the onward study of the subject by researchers; 2) evaluating the specific factors that predict the adoption and acceptance of technologies in construction research thus allowing for an expanded understanding of construction practitioners inherent behaviors critical to decision-making, and; (3) developing critical insight needed to guide the quality of future studies on forecasting technological applications in construction practice.

However, this study has a few limitations some of which are common to most review studies. For instance, a few relevant articles could have been inadvertently missed even with the fact that a systematic process was followed to identify useful papers within the scope of the study. In addition, this study limited the sources of information to journal papers using an established criterion and did not consider conference papers, reports, and online materials that could provide more insights into technology acceptance. In spite of these identified limitations, this study contributes to an incisive understanding of the current state of the technology integration process in the construction industry.

References

Abbasi, M. S., Tarhini, A., Elyas, T., & Shah, F. (2015). Impact of individualism and collectivism over the individual's technology acceptance behavior. *Journal of Enterprise Information Management.*

Aroke, O., Hasanzadeh, S., Esmaeili, B., Dodd, M. D., & Brock, R. (2022). Using Worker Characteristics, Personality, and Attentional Distribution to Predict Hazard Identification Performance: A Moderated Mediation Analysis. *Journal of Construction Engineering and Management*, *148*(6), 04022033.

Awolusi, I., Marks, E., & Hallowell, M. (2018). Wearable technology for personalized construction safety monitoring and trending: Review of applicable devices. *Automation in construction*, 85, 96-106.

Ayodele, O. A., Chang-Richards, A., & González, V. (2020). Factors affecting workforce turnover in the construction sector: a systematic review. *Journal of Construction Engineering and Management*, 146(2), 03119010.

Chau, P. Y., & Hu, P. J. H. (2001). Information technology acceptance by individual professionals: A model comparison approach. *Decision sciences*, 32(4), 699-719.

Chen, J., Ha, N. T. T., Tai, H., & Chang, C. (2020). The willingness to adopt the internet of things (IoT) conception in taiwan's construction industry. *Journal of Civil Engineering and Management*, 26(6), 534-550. doi:10.3846/jcem.2020.12639

Cheng, J. C., Chen, K., & Chen, W. (2020). State-of-the-art review on mixed reality applications in the AECO industry. *Journal of Construction Engineering and Management*, 146(2), 03119009.

Chin, W., Cheah, J. H., Liu, Y., Ting, H., Lim, X. J., & Cham, T. H. (2020). Demystifying the role of causal-predictive modeling using partial least squares structural equation modeling in information systems research. Industrial Management and Data Systems.

Choi, B., Hwang, S., & Lee, S. (2017). What drives construction workers' acceptance of wearable technologies in the workplace?: Indoor localization and wearable health devices for occupational safety and health. *Automation in Construction*, 84, 31-41. doi:10.1016/j.autcon.2017.08.005

Darko, A., Chan, A. P., Owusu-Manu, D. G., & Ameyaw, E. E. (2017). Drivers for implementing green building technologies: An international survey of experts. *Journal of cleaner production*, *145*, 386-394.

Davis, F. D. (1989). Perceived usefulness, perceived ease of use, and user acceptance of information technology. *MIS quarterly*, 319-340.

Davis, F. D., Bagozzi, R. P., & Warshaw, P. R. (1989). User acceptance of computer technology: a comparison of two theoretical models. Management science, 35(8), 982-1003.

El-Omari, S., & Moselhi, O. (2011). Integrating automated data acquisition technologies for progress reporting of construction projects. *Automation in Construction*, 20(6), 699-705.

Esmaeili, B., & Hallowell, M. R. (2012). Diffusion of safety innovations in the construction industry. *Journal of Construction Engineering and Management*, 138(8), 955-963.

Green, S. (2011). Making sense of construction improvement. Chichester: Wiley-Blackwell.

Harty, C. (2008). Implementing innovation in construction: contexts, relative boundedness and actor-network theory. Construction management and economics, 26(10), 1029-1041.

Hu, X., Chong, H. Y., Wang, X., & London, K. (2019). Understanding stakeholders in off-site manufacturing: a literature review. *Journal of Construction Engineering and Management*, 145(8), 03119003.

Jin, R., Zou, Y., Gidado, K., Ashton, P., & Painting, N. (2019). Scientometric analysis of BIM-based research in construction engineering and management. *Engineering, Construction and Architectural Management.*

Kim, S., Moore, A., Srinivasan, D., Akanmu, A., Barr, A., Harris-Adamson, C., ... & Nussbaum, M. A. (2019). Potential of exoskeleton technologies to enhance safety, health, and performance in construction: Industry perspectives and future research directions. *IISE Transactions on Occupational Ergonomics and Human Factors*, *7*(3-4), 185-191.

Lee, S., & Yu, J. (2020). Longitudinal Study on Construction Organization's BIM Acceptance. *Applied Sciences*, 10(15), 5358.

Lee, S., and Yu, J. (2017). Discriminant model of BIM acceptance readiness in a construction organization. *KSCE Journal of Civil Engineering*, 21(3), 555-564.

Lee, S., Yu, J., &and Jeong, D. (2015). BIM acceptance model in construction organizations. *Journal of management in engineering*, 31(3), 04014048.

Liu, L. X., & Liu, L. (2017). Evidence on innovation in public-private partnership project. *In European Conference on Innovation and Entrepreneurship (pp. 375-383). Academic Conferences International Limited.*

Martínez-Rojas, M., Marín, N., & Vila, M. A. (2016). The role of information technologies to address data handling in construction project management. *Journal of Computing in Civil Engineering*, 30(4), 04015064.

Mun, Y. Y., Jackson, J. D., Park, J. S., & Probst, J. C. (2006). Understanding information technology acceptance by individual professionals: Toward an integrative view. *Information and Management*, 43(3), 350-363.

Nnaji, C., Okpala, I., & Kim, S. (2019). A simulation framework for technology adoption decision making in construction management: A composite model. *In Computing in civil engineering 2019: Visualization, information modeling, and simulation (pp. 499-506). Reston, VA: American Society of Civil Engineers.*

Ogunrinde, O., Nnaji, C., & Amirkhanian, A. (2020). Quality Management Technologies in Highway Construction: Stakeholders' Perception of Utility, Benefits, and Barriers. *Practice Periodical on Structural Design and Construction*, 26(1), 04020043.

Okpala, I., Nnaji, C., & Awolusi, I. (2022). Wearable sensing devices acceptance behavior in construction safety and health: assessing existing models and developing a hybrid conceptual model. *Construction Innovation*, *22*(1), 57-75.

Okpala, I., Nnaji, C., & Karakhan, A. A. (2020). Utilizing emerging technologies for construction safety risk mitigation. *Practice Periodical on Structural Design and Construction*, 25(2), 04020002.

Omachonu, V. K., & Einspruch, N. G. (2010). Innovation in healthcare delivery systems: a conceptual framework. *The Innovation Journal: The Public Sector Innovation Journal*, 15(1), 1-20.

Owolabi, J. D., Faleye, D., Eshofonie, E. E., Tunji-Olayeni, P. F., & Afolabi, A. O. (2019). Barriers and drivers of innovation in the Nigerian construction industry. *International Journal of Mechanical Engineering and Technology (IJMET)*, 10(02), 334-339.

Ozorhon, B. (2013). Analysis of construction innovation process at project level. *Journal of management in engineering*, 29(4), 455-463.

Rahman, M. M., Lesch, M. F., Horrey, W. J., & Strawderman, L. (2017). Assessing the utility of TAM, TPB, and UTAUT for advanced driver assistance systems. Accident Analysis and Prevention, 108, 361-373.

Sainani, K. L. (2014). Explanatory versus predictive modeling. *PMandR*, 6(9), 841-844.

Sepasgozar, S. M., Ghobadi, M., Shirowzhan, S., Edwards, D. J., & Delzendeh, E. (2021). Metrics development and modelling the mixed reality and digital twin adoption in the context of Industry 4.0. *Engineering, Construction and Architectural Management.*

Sepasgozar, S. M., Loosemore, M., & Davis, S. R. (2016). Conceptualising information and equipment technology adoption in construction. *Engineering, Construction and Architectural Management*.

Shmueli, G., & Koppius, O. R. (2011). Predictive analytics in information systems research. *MIS quarterly*, 553-572.

Shen, X., Awolusi, I., & Marks, E. (2017). Construction equipment operator physiological data assessment and tracking. *Practice Periodical on Structural Design and Construction*, *22*(4), 04017006.

Sherratt, F., Dowsett, R., & Sherratt, S. (2020). Construction 4.0 and Its Potential Impact on People Working in the Construction Industry. *Proceedings of the Institution of Civil Engineers-Management, Procurement and Law*, 1-8.

Siraj, N. B., & Fayek, A. R. (2019). Risk identification and common risks in construction: Literature review and content analysis. *Journal of Construction Engineering and Management*, 145(9), 03119004.

Slaughter, E. S. (2000). Implementation of construction innovations. *Building research and information*, 28(1), 2-17.

Son, H., Park, Y., Kim, C., & Chou, J. (2012). Toward an understanding of construction professionals' acceptance of mobile computing devices in south korea: An extension of the technology acceptance model. *Automation in Construction*, 28, 82-90.

Taherdoost, H. (2018). A review of technology acceptance and adoption models and theories. *Procedia manufacturing*, 22, 960-967.

Tarhini, A., Arachchilage, N. A. G., &and Abbasi, M. S. (2015). A critical review of theories and models of technology adoption and acceptance in information system research. *International Journal of Technology Diffusion (IJTD)*, 6(4), 58-77.

Uusitalo, P., Olivieri, H., Seppänen, O., Pikas, E., & Peltokorpi, A. (2017). Review of lean design management: processes, methods and technologies. In *Proceedings of the 25th annual conference of the international group for lean construction, Heraklion, Greece (pp. 571-578).*

Venkatesh, V., & Davis, F. D. (2000). A theoretical extension of the technology acceptance model: Four longitudinal field studies. *Management science*, 46(2), 186-204.

Venkatesh, V., Morris, M. G., Davis, G. B., & Davis, F. D. (2003). User acceptance of information technology: Toward a unified view. *MIS quarterly*, 425-478.

Wang, G., Wang, P., Cao, D., & Luo, X. (2020). Predicting behavioural resistance to BIM implementation in construction projects: An empirical study integrating technology acceptance model and equity theory. *Journal of Civil Engineering and Management*, 26(7), 651-665.

Williams, M. D., Rana, N. P., & Dwivedi, Y. K. (2015). The unified theory of acceptance and use of technology (UTAUT): a literature review. *Journal of enterprise information management*.

A Review of Life Cycle Assessment Tools for Measuring the Environmental Impact of Building and a Decision Support Framework for Choosing Among Them

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Abstract: The increased environmental concerns in recent decades have resulted in examining waste emissions, resource utilization, and resource depletion. A holistic environmental assessment should consider all these factors. Researchers, policymakers, and companies are paying more attention to environmental management. As a result, organizations are developing their environmental practices to enhance environmental management throughout the building life cycle. Contemporary life cycle assessment (LCA) stands out as a reliable and comprehensive method that effectively communicates such benefits to stakeholders and offers them more leverage. LCA is increasingly being used to assess how construction processes affect the environment and minimize these impacts. There is a need for research on the use of LCA tools in buildings, which is a key point and a solution to facilitate environmental management practices and transform the construction industry. Based on a literature review, the research studies LCA tools for quantifying buildings' environmental impact and provides a decision support framework for choosing LCA tools. The paper aims to analyze the current uses of LCA in construction, present LCA tools, compare applied tools in buildings, and explore three commonly used LCA tools for building studies. Moreover, this research explores that managing the database is one of the most significant issues with current LCA tools. It suggests that building information modeling (BIM) and LCA integration is an approach that might facilitate and simplify data management for LCA analysis throughout all building life cycles. This study's results will assist project stakeholders in choosing the appropriate tools and selecting the most environmentally friendly products at different building life cycle stages (i.e., design, construction, and maintenance) for the project's success.

Key words: Life cycle assessment tools, LCA applications, building, construction, environmental impact of buildings, life-cycle analysis.

Introduction

Today, built environments consume large amounts of energy and resources, harming human health and the natural ecosystem (Ansah et al., 2021). As stated in *Architecture2030* (2022), greenhouse gas emissions (GHGs) come mainly from the built environment, which is responsible for up to 50% of all carbon dioxide (CO_2) emissions globally. Buildings caused the most significant impacts, primarily due to the massive amounts of raw materials consumed by construction activity. The building industry uses about 40% of the world's materials annually (Ansah et al., 2021). Therefore, the industry must find environmentally friendly answers to environmental problems that also enable decreased material and energy usage throughout a building's life cycle. As a result, evaluations and analyses of a building's energy and environmental performance need to evaluate its entire life cycle using internationally accepted methods such as the life cycle assessment (Ansah et al., 2021). Life cycle assessment is an analytical methodology for quantifying the environmental impact of processes and products over their life cycle. (Dalla Mora et al., 2020). This method is getting more attention through construction technology advancements and integrated design processes (Srinivasan et al., 2014). In the opinion of studies, at the product level, LCA can quantify the product's energy consumption and environmental impacts from the cradle to the grave. At the building level, it can be used to compare the environmental impacts of different building designs and choose the alternative with the least impact. Corresponding to ISO 14040 (2006), LCA analyses potential environmental impacts from the procurement of raw materials through production, use, and disposal. It also evaluates the construction, ownership, and disposal costs involved with building systems (Han & Srebric, 2011). Accordingly, both academia and the construction industry have been developing approaches to apply LCA to buildings. In conducting this review, this research attempts to answer the following key questions: (RQ1) What is the current state of LCA? (RQ2) What research on LCA tools is available? and (RQ3) What are the best LCA tools used in buildings?

Background

Life cycle assessment studies the overall environmental impacts of buildings across their life cycles. Chau et al. (2015) describe LCA as an objective approach for analyzing the environmental burdens associated with recognizing and measuring the impact of a product, process, or activity on the environment in terms of energy, materials, and emissions; and, finally, developing and implementing measures to reduce or eliminate these impacts. The International Organization for Standardization (ISO) has advanced LCA standards to address a project's technical and administrative concerns. The LCA general methodology follows the four-stage framework recommended by ISO 14040 (2006) and ISO 14044 (2006). The four stages are (1) goals and scope definition, (2) life cycle inventory (LCI), (3) life cycle assessment (LCA), and (4) interpretation. In particular, standard EN 15978 (2011) is a reference for calculating the environmental impacts of buildings and evaluating the flow of materials, resources, energy consumption, and emissions that are released into the environment. It is organized according to the building's life cycle, which includes production, construction, usage, and end-of-life phases. LCA is a reliable environmental management technique, and it has the potential to evaluate alternatives (Abd Rashid & Yusoff, 2015). Databases, methodologies, and impact assessment models have been created and implemented in specialized software tools that contribute to the LCA results. In the existing literature, only a limited number of studies have tried to compare outcomes using several LCA software tools in buildings. It is essential to choose suitable LCA tools since they can affect results and decisions during the building life cycle (Silva, Nunes et al., 2019).

Methodology

This study's methodology provided a set of data analyses to present the qualitative approach through concepts and experiences, as well as insight into scholarly publications. Initially, data was gathered from a variety of sources. The original search keywords were "life cycle assessment tools, LCA applications, building, construction, the environmental impact of buildings, and life cycle analysis." The initial literature review identified research gaps and emerging trends in relevant LCA topics within the construction industry. This step helped the researcher become familiar with the current state of knowledge and the constraints of a particular topic. Second, this extensive literature review attempted to answer the research questions raised above about the concept of LCA and discussed the similarities and differences between these tools. The study provided a basic knowledge of LCA tools and suggested eight criteria for the LCA analysis. These criteria were used as a filter in the decision support framework, which will assist stakeholders in deciding LCA tools for buildings. Lastly, the research applied the proposed criteria to compare three examples of digital LCA tools, including the

Athena Impact Estimator, EC3, and Tally. The study delivered a roadmap for academic researchers who will continue analyzing and comparing LCA tools using the suggested methodology.

Review of Life Cycle Assessment tools in construction

The first review of notes in this area was by Al-Ghamdi & Bilec (2016). The research included a comparative analysis to evaluate the commercial LCA tools. These tools were accessible to designers throughout various phases of the design process, and they could be used to meet the requirements of multiple green building rating systems (GBRS). Global warming potential is a required category in comparison to a baseline building. The impact category and material takeoff accuracy influence the LCA software effect. Given the same building, the LCA results produced by the three different software tools varied in both the embedded impacts (such as metal, concrete, masonry, etc.) and the operational impacts (for example, area lights, exterior loads, heat rejection, etc.). The paper recommended refining LCA methodologies for GBRS and obtaining more comprehensive data sets for building systems and products. Similarly, Jrade & Abdulla (2012) reviewed the LCA, BIM, and data exchange standards that could facilitate integrating them. The paper chose the EcoCalculator as a tool and Autodesk Revit as BIM software because of their widespread use by architectural engineering and construction (AEC) professionals, which enables them to reduce learning and development costs, especially in the early planning stages. As a result, the authors recommend dividing LCA tools into three categories: (1) product comparison tools for LCA and non-LCA practitioners; (2) whole process construction tools; and (3) comprehensive assessment and rating frameworks. According to the study, future LCA implementation should consider significant factors such as building type, geographic location, and data source.

Nine out of the 15 papers mentioned literature review as a research methodology. One study chose to use the experimentation and case study methods. Through a literature review, Bueno & Fabricio (2016) suggested adding LCA databases to the Building Information Modeling (BIM) platform, which is used in the design process. The research considered the plug-in Tally as the simplification and friendly use, which included identifying the most prominent environmental impacts and how impacts can be compared among the different materials options concerning energy consumption operations. By doing that, the result was the LCA on demand and an environmental information layer for decision-making in the same building design software. In agreement with Antón (2013), the study introduced the integration of BIM and LCA as tools to achieve sustainable construction. The research presented potential solutions, focusing on their contribution to sustainability to understand the construction industry and building sector's main features and existing problems. The investigation focused on the design phase since it may have the greatest impact. The research recommended criteria for assessing the cases studied based on the analysis with LCA software developers. The author also concluded that the availability of databases is one of the main difficulties when developing an LCA of buildings. Similarly, Dalla Mora et al. (2020) reviewed the state of the art of research published in the past ten years on integrating BIM-LCA as a method whereby the BIM approach might facilitate and simplify data management for LCA analysis. Based on their specific objectives and the available data, the research established a framework of all available adopted methodologies in the science community to assist designers in making appropriate decisions. In the future, researchers will find a way to link the BIM integration of impact data with the requirements for building labels or rating systems that are either required or optional. Complex workflows will be one of the most developed scenarios in future research regarding the interoperability of BIM, especially in developing tools and methodologies to enable automatic quantity takeoff. Dalla Mora et al. (2020) successfully presented evidence of a general heterogeneous framework to define the common and widespread approaches to identifying building factors that were considered in applying the BIM-LCA integration.

Rossi et al. (2012), Han & Srebric (2011), Lopes Silva et al. (2019), and Srinivasan et al. (2014) used case studies as research methodology and reviewed different LCA software tools. Rossi et al. (2012) described and applied some LCA tools to achieve the complete LCA of residential buildings in three European towns. Rossi et al. (2012) also identified some building characteristics to consider when choosing an LCA. Concurrently, Han & Srebric (2011) introduced different LCA tools: BEES, Athena Eco Calculator, Athena Impact Estimator, and SimaPro. The paper discussed these tools in terms of performance and environmental impact analysis to help users choose appropriate tools for project analysis. Lopes Silva et al. (2019) presented the differences in LCA results due to using various LCA software tools for the same product system. After performing a cause-effect analysis of the problem, the authors found two root causes: (1) the import process for background datasets and (2) the lack of rules for implementing life cycle inventory analysis (LCIA) methods in the software tools. The main findings of this work uncover different numbers of characterization factors and sub-compartments in each software tool for each impact category that can generate different LCA results. Srinivasan et al. (2014) conducted a case study that applied two existing LCA tools: an economic input output-based (EIO LCA) model and a process-based model (as Athena), to estimate life-cycle energy use in an example building. The comparison was centered on the energy-based indicators used. The authors explored whether these LCA tools could help enrich sustainability-related decision-making in building design, construction, operation, and decommissioning. Future researchers should put more effort into tracking data at all stages of the building life cycle, including the end-of-life stage, which currently needs more research.

Each project is unique, and every building project has different characteristics to consider when implementing a life cycle assessment (Rossi et al., 2012). Consequently, the paper discussed each section, highlighting how previous researchers developed the life cycle assessment concept while identifying objectives, methods, challenges, and findings, thus supporting future work. As a result, the current state of LCA tools was analyzed, synthesized, and summarized from the reviewed literature. All the tools can be helpful for their particular purpose, provided the user understands their potential limitations. The suitability of one software program relative to another depends on the user's scope or objectives, system level, and building location, and the database of each program could be different (Ormazabal et al., 2014). Accordingly, given that different projects have various objectives, stakeholders should define the expected results and details of interest for each project before starting life cycle analyses to choose the right tool (Han & Srebric, 2011). Completing an LCA at different system levels (i.e., materials, components, structures, portions, or the entire building), especially a whole building analysis, is time and resource-intensive. The above papers have touched on key areas relating to data resources and associated LCA digital methods in the building life cycle.

Comparative analysis of selected LCA tools

This study chose digital methods (including tools, applications, and software) to advance the LCA in buildings. The concept of digital technology is to build a three-dimensional (3D) virtual representation of a building; thus, building components can be planned and evaluated before actual construction. The 3D virtual model helps improve documentation quality, increases productivity, and improves visibility while minimizing adverse environmental impact. BIM is the best choice for stimulating LCA, as BIM is one of the options for calculating life-cycle assessment and energy consumption (Jrade & Abdulla, 2012). The BIM model contains geometric and functional properties of intelligent objects for visualization and simulation to facilitate the interdisciplinary flow of information and data for building projects over their life cycle. The researchers selected three examples of digital LCA tools: the Athena Impact Estimator, EC3, and Tally. These tools are intended to assess buildings and other elements that form part of the built environment. They generally focus on energy and emissions. In addition, they considered the depletion of natural resources, waste production, water consumption, the release of pollutants, and human health impacts. They are three of the most prominent applications, giving the program high visibility and reliability, thereby enhancing its chances of distribution. As shown in Table 1, different parameters were adopted to evaluate the state of the art regarding selected LCA tools. The direct comparison of these tools includes their tool description, purposes, license cost, pros, and cons. This approach also adds a basic understanding of LCA tools to help facilitate decision-making.

Table 1.
Basic Comparison of selected LCA Tools

#	Parameters	EC3 tool (Embodied Carbon)	Tally (App in Revit)	Athena Impact Estimator
1	Description	An open-access tool by Skanska (US) and Change Labs in partnership with Microsoft, Autodesk	Revit Plugin LCA Tool developed by Kieran Timberlake (US) in partnership with Sphera and Autodesk (2014)	Desktop LCA Tool developed by Athena Sustainable Materials Institute (Canada, 2002)
2	Purposes	Allows benchmarking, assessment & reductions in embodied carbon CO2 Used for supply chain emissions of materials	Quantifies the environmental impact of building materials for whole building analysis and comparative design options.	Explores the environmental impact of different material choices and core-and-shell system options.
3	Cost	Free Software	Not free (requires Revit)	Free Software
4	Pros	Simple visualization of a project's potential and realized embodied carbon impacts.	Easy to use Requires no special expertise The result is on demand Allows designers to evaluate various design options	Allows users to include energy simulation results to calculate operating energy effects alongside the effects of embodied energy
5	Cons	Works best in the design stage and construction stage only.	Interprets difficulty the LCA results	Technical knowledge of the building construction is required for data input.

*The information in the table is from each tool's technical documentation, which was based on the authors' insights gained from reviewing the developers' technical reports.

Criteria Proposal

Each building has different characteristics that could influence the selection of appropriate LCA tools. By conducting a literature review of published studies and expanding upon the framework proposed by Dalla Mora et al. (2020), this research suggested eight criteria regarding the LCA analysis, as shown in Table 2. Selection criteria added a filter for study characteristics that helped determine whether they should be included, allowing researchers to better analyze the data. These criteria served as the attributes in the decision support framework, which thereafter will support stakeholders in making transparent decisions on selecting LCA tools in a construction project.

A description of eight criteria:

1. Design stage: refers to the five phases of a design project, which are schematic design, design development, construction documents, bidding, and construction administration.
2. Development Level: This specifies the degree of the building component's specifications, the geometry of its attached information, and (2) the level of frequency of update.
3. Integration Tools: integrate with other standard design software to create a building model, a quantity take-off, a bill of materials, and data exchange.
4. Impacts category (or environmental impact categories): shows the potential impact of a given life cycle impact assessment (LCIA) methodology.
5. Learning curve: (1) time required to develop the LCA model, analyze alternate design options, and update the LCA results; and (2) ease of use of the software.

6. Database: digital data includes environmental information for building materials. It determines the LCA analysis and the evaluation of each building component.
7. LCA Phase: describes the different building life cycles in the analysis as defined by EN 15978.
8. Reporting results: can be (1) extracted as an LCA report for reporting purposes by illustrating results, or (2) produced as design option comparisons within the software.

Table 2.
Analysis Criteria for choosing LCA tools

	Propose the Criteria in literature review of related topic	Al-Ghamdi & Bilec (2016)	Ansah et al. (2021)	Antón (2013)	Battisti et al. (2019)	Bueno & Fabricio (2016)	Chau et al. (2015)	Dalla Mora et al. (2020)	Han & Srebric (2011)	Lopes Silva et al. (2019)	Jrade & Abdulla (2012)	Rossi et al. (2012)	Singh et al. (2011)	Silva et al. (2009)	Srinivasan et al. (2014)	Ormazabal et al. (2014)
1	Design Stage	✓		✓	✓	✓	✓	✓			✓	✓			✓	
2	Level of Development	✓	✓			✓		✓	✓					✓	✓	
3	Integration Tools	✓	✓			✓	✓	✓	✓	✓	✓			✓		✓
4	Impact Category	✓	✓		✓	✓	✓		✓	✓	✓	✓	✓			✓
5	Learning Curve	✓	✓	✓	✓	✓		✓	✓	✓	✓			✓		✓
6	Database	✓	✓	✓	✓	✓		✓		✓		✓	✓			✓
7	LCA Phase	✓	✓				✓				✓	✓				
8	Reporting Results	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Summary	8	7	4	5	7	5	6	5	5	6	5	3	4	3	5

*The number of ticks for each LCA publication shows their contributions in terms of the study's proposed criteria.

Our research has applied the proposed criteria, expanding upon the framework suggested by Anthony Pak & Farzad Jalalei (2019), to compare the three most widely used LCA tools, including EC3, Tally, and Athena. The comparison results are shown in Table 3.

Table 3.
Comparison of selected LCA Tools based on the proposed Criteria

#	Analysis Criteria	EC3 tool (Embodied Carbon)	Tally (App in Revit)	Athena Impact Estimator
1	Design Stage	Construction documents. Bidding. Construction admin.	Schematic design. Design development. Construction documents.	Schematic design, Design development, Construction documents, Bidding & Construction admin.
2	Level of Development	The EC3 tool uses third-party verified EPD entries. The number of product categories have limited. Provide inaccurate estimates for materials.	Updates annually. Develops new features. Mapping from Revit elements. Need to model design options in Revit software.	Updates data annually. Not provide new features or user interface. Develops alternatives of material or assembly options.
3	Integration Tools	Integrates with Revit, Excel, etc. Automatically takeoffs from Revit model	Integrates with EC3 tool to compare manufacturer specific EPDs. No spreadsheet import of material quantities.	No Revit/BIM plugin is available Manual takeoffs from drawings and updating takeoffs

		Use generic product category EPD (before products are specified)		Excel for importing material quantities.
4	Impact Category	Embodied Carbon for Global Warming Potential	Global Warming Potential Acidification Potential Eutrophication Potential Ozone Depletion Potential Smog Formation Potential Primary Energy Demand Non-renewable Energy	Global Warming Acidification Human Health Respiratory Effects Ozone Depletion Photochemical Smog Eutrophication Fossil Fuel Consumption
5	Learning curve	Users can quickly provide owners with the information they need to set embodied carbon performance targets.	Easy to learn mapping functionality. Requires Revit knowledge Define relationships between BIM elements and construction materials from the Tally database.	Easy to learn the basics Extensive help file documentation. Customize the model of assemblies and envelope Provides flexibility for design options .
6	Database	Bases on EPD data. Data entry without BIM import is heavy. Materials must be entered by weight and volume, not length or surface area.	Relies on GaBi background Mostly industry average data manufacturer specific EPD Has no regionalization data assumptions for the U.S.	Relies on Ecoinvent background. Mostly industry average data. Limited manufacturer data. Regionalized assumptions for Canadian and the U.S.
7	LCA Phase	Production	Production, Construction, Use & End of life	Production, Construction, Use & End of life
8	Reporting Results	Enables the visualization of a project's potential. Realizes embodied carbon impacts. Understand the baselines. Sets reduction targets. Provides several carbon benchmarks for a project on the same design.	Provides detailed report generated for LEED submission, which includes graphs and an excel sheet. Has a detailed estimation of material quantities. Challenging to model option material/ assembly options .	Generates LEED results reports with basic graphs and Excel exports. Results are aggregated by element and cannot be disaggregated to show the contribution of individual materials or assemblies.

*EPD - Environmental Product Declarations; *LEED - Leadership in Energy and Environmental Design.
The data information is collected to identify these technologies based on the authors' insights gained from reviewing the developers' technical reports and personal practice experiences.

Results and Discussions

The study investigated common challenges encountered while implementing the LCA framework based on a thorough literature review. Subsequently, managing the database is one of the most significant issues with current LCA tools. The database needs reliability, completeness, and consistency associated with the software outputs. The database includes the volume, quality, accuracy, and relevance of data available to the user in the software (Ormazabal et al., 2014). EPD's limitations provide environmental information that does not allow direct comparison or choice of construction products. Thus, the insertion of LCA data into models developed in the BIM platform would facilitate the implementation of such a quantitative environmental assessment methodology in the construction field (Bueno & Fabricio, 2016). Another challenge was that data for various geographical areas or building locations are needed to achieve global practical tools (Antón, 2013). Most existing LCA tools contained data or parameters that restricted the tool's use to a particular geographic or regional location (Han & Srebric, 2011). Using data not representative of the analyzed product could be challenging because the impacts of similar products in different countries can differ significantly. It was due to different production processes, transportation distances, and the source of raw materials. For some tools, it was possible to link to additional databases more representative of locations, processes, or other characteristics of the product being analyzed. The selection of commercially available tools was an additional obstacle for designers.

The tools vary systematically in how they are built, the user skills required, and the design stage at which they can be used (Al-Ghamdi & Bilec, 2016). Necessarily, the industry needs to take an active interest in developing common databases, and research is needed to develop and implement protocols for collecting, verifying, gathering, synthesizing, updating, and summarizing this data into a usable form (Singh et al., 2011). Respectively, the four objectives were achieved, including (1) analyzing the current uses of LCA in construction, (2) presenting LCA tools, (3) comparing applied tools in buildings, and (4) exploring three commonly used LCA tools for building studies. Three questions were addressed: the current state of LCA, the available research on LCA tools, and the best suitable LCA tools used in buildings. In this paper's scope, the research methodology's design did not cover all aspects of LCA methodologies, thus, it left some trails around the topic. A complete building LCA of future research will include an evaluation of the impacts of all resource needs, inputs, and outputs at each stage of the building life cycle. Also, time and resources limited the number of related publications and articles. LCA wasn't readily implemented because of several limitations such as system boundaries, selection availability, quality data sources, and geographic data. The assessment was as data-based as possible and relied on hypotheses and estimates, which should be studied further in future research.

Conclusions

This research contributes to the body of knowledge by examining LCA methodologies and developing the criteria for choosing appropriate LCA methods, including the design stage, level of development, integration tools, impact category, learning curve, database, LCA phase, and reporting results. The study adopted and built upon the framework developed by Dalla Mora et al. (2020). Most significantly, the framework proposed in our research advanced the prior works by adding the following three criteria: learning curve, integration, and reporting results. In addition, this research applied our proposed framework to compare the three most widely used LCA tools, including EC3, Tally, and Athena. This research benefits practitioners and researchers by providing a road map to continue analyzing and comparing different LCA tools (e.g., OneClick LCA, SimaPro, or BEES) using the proposed framework. Additionally, this research concluded that the current BIM and LCA integration is limited to the design and construction phases due to their generic data. Future research is needed to expand further and enhance the integration of BIM and LCA throughout all building life cycles, including operation, maintenance, demolition, and recycling or reuse. Meeting sustainability standards in design is a common source of difficulty for experts (Dalla Mora et al., 2020). New buildings should be designed with environmental friendliness and energy efficiency in mind. LCA is among the different methods developed to assess environmental performance and reduce its impacts. Ultimately, several studies have emphasized incorporating LCA into the building design process as early as possible (Battisti et al., 2019) using adaptable, user-friendly technologies connected to current digital data databases.

References

Abd Rashid, Ahmad Faiz, and Sumiani Yusoff. 2015. "A Review of Life Cycle Assessment Method for Building Industry." *Renewable and Sustainable Energy Reviews* 45:244–48. doi: 10.1016/j.rser.2015.01.043.

Al-Ghamdi, Sami G., and Melissa Bilec. 2016. "Green Building Rating Systems and Whole-Building Life Cycle Assessment: Comparative Study of the Existing Assessment Tools." *Journal of Architectural Engineering* 23:04016015. doi: 10.1061/(ASCE)AE.1943-5568.0000222.

Ansah, Mark Kyeredey, Xi Chen, Hongxing Yang, Lin Lu, and Patrick T. I. Lam. 2021. "Developing an Automated BIM-Based Life Cycle Assessment Approach for Modularly Designed High-Rise Buildings." *Environmental Impact Assessment Review* 90:106618. doi: 10.1016/j.eiar.2021.106618.

Anthony Pak and Farzad Jalalei. 2019. “Priopta | Building Life Cycle Assessment (LCA) | Canada.” Retrieved October 29, 2022 (https://www.priopta.com/).

Antón, Laura Álvarez. 2013. “Integration of LCA and BIM Considering Early Building/Construction Design Stages.” *Undefined*.

Architecture2030. 2022. “Why The Building Sector? – Architecture 2030.” Retrieved October 28, 2022 (https://architecture2030.org/why-the-building-sector/).

Battisti, Alessandra, Sandra G. L. Persiani, and Manuela Crespi. 2019. “Review and Mapping of Parameters for the Early Stage Design of Adaptive Building Technologies through Life Cycle Assessment Tools.” *Energies* 12(9):1729. doi: 10.3390/en12091729.

Bueno, Cristiane, and Márcio Fabricio. 2016. “Application of Building Information Modelling (BIM) to Perform Life Cycle Assessment of Buildings.” *Pós. Revista Do Programa de Pós-Graduação Em Arquitetura e Urbanismo* 23:96–121. doi: 10.11606/issn.2317-2762.v23i40p96-121.

Chau, C. K., T. M. Leung, and W. Y. Ng. 2015. “A Review on Life Cycle Assessment, Life Cycle Energy Assessment and Life Cycle Carbon Emissions Assessment on Buildings.” *Applied Energy* 143:395–413. doi: 10.1016/j.apenergy.2015.01.023.

Dalla Mora, Tiziano, Erika Bolzonello, Carmine Cavalliere, and Fabio Peron. 2020. “Key Parameters Featuring BIM-LCA Integration in Buildings: A Practical Review of the Current Trends.” *Sustainability* 12(17):7182. doi: 10.3390/su12177182.

Han, Guiyuan, and Jelena Srebric. 2011. “Life-Cycle Assessment Tools for Building Analysis.” 7.

Jrade, Ahmad, and Raidan Abdulla. 2012. “Integrating Building Information Modeling And Life Cycle Assessment Tools To Design Sustainable Buildings.”

Lopes Silva, Diogo Aparecido, Andréa Oliveira Nunes, Cassiano Moro Piekarski, Virgínia Aparecida da Silva Moris, Luri Shirosaki Marçal de Souza, and Thiago Oliveira Rodrigues. 2019. “Why Using Different Life Cycle Assessment Software Tools Can Generate Different Results for the Same Product System? A Cause–Effect Analysis of the Problem.” *Sustainable Production and Consumption* 20:304–15. doi: 10.1016/j.spc.2019.07.005.

Ormazabal, Marta, Carmen Jaca, and Rogério Puga-Leal. 2014. “Analysis and Comparison of Life Cycle Assessment and Carbon Footprint Software.” Pp. 1521–30 in *Advances in Intelligent Systems and Computing*. Vol. 281.

Rossi, Barbara, Anne-Françoise Marique, Mauritz Glaumann, and Sigrid Reiter. 2012. “Life-Cycle Assessment of Residential Buildings in Three Different European Locations, Basic Tool.” *Building and Environment* 51:395–401. doi: 10.1016/j.buildenv.2011.11.017.

Silva, Vanessa, Natália Barros, and Regina Ruschel. 2019. “Building Information Modelling for Whole-Building LCA: BIM4LCA.” *IOP Conference Series: Earth and Environmental Science* 290:012044. doi: 10.1088/1755-1315/290/1/012044.

Singh, Amanjeet, George Berghorn, Satish Joshi, and Matt Syal. 2011. “Review of Life-Cycle Assessment Applications in Building Construction.” *Journal of Architectural Engineering* 17(1):15–23. doi: 10.1061/(ASCE)AE.1943-5568.0000026.

Srinivasan, Ravi S., Wesley Ingwersen, Christian Trucco, Robert Ries, and Daniel Campbell. 2014. “Comparison of Energy-Based Indicators Used in Life Cycle Assessment Tools for Buildings.” *Building and Environment* 79:138–51. doi: 10.1016/j.buildenv.2014.05.006.

A Review of Life Cycle Assessment Tools for Measuring the Environmental Impact of Building and a Decision Support Framework for Choosing among them

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Problem Statement - Research Significance

- The increased environmental concerns in recent decades have resulted in examining waste emissions, resource utilization, and resource depletion. A holistic environmental assessment should consider all these factors.
- Researchers, policymakers, and companies are paying more attention to environmental management. As a result, organizations are developing their environmental practices to enhance environmental management throughout the building life cycle.
- Contemporary life cycle assessment (LCA) stands out as a reliable and comprehensive method that effectively communicates such benefits to stakeholders and offers them more leverage. LCA is increasingly being used to assess how construction processes affect the environment and minimize these impacts.
- There is a need for research on the use of LCA tools in buildings, which is a key point and a solution to facilitate environmental management practices and transform the construction industry.

Production			Construction		Use							End of Life				Module
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C12	C3	C4	D
Raw materials supply	Transport (to factory)	Manufacturing	Transport (to site)	Construction	Use	Maintenance	Repair	Replacement	Refurbishment	Operational Energy Use	Operational Water Use	De-Construction Demolition	Transport (To disposal)	Waste Processing	Disposal	Benefits & Loads beyond the system boundary: Reuse, Recovery,

Figure 1. *Building life cycle, adapted from EN 15978 (2011)*

Table 1.
Basic Comparison of selected LCA Tools

#	Parameters	EC3 tool (Embodied Carbon)	Tally (App in Revit)	Athena Impact Estimator
1	Description	An open-access tool by Skanska (US) and Change Labs in partnership with Microsoft, Autodesk	Revit Plugin LCA Tool developed by Kieran Timberlake (US) in partnership with Sphera and Autodesk (2014)	Desktop LCA Tool developed by Athena Sustainable Materials Institute (Canada, 2002)
2	Purposes	Allows benchmarking, assessment & reductions in embodied carbon CO2 Used for supply chain emissions of materials	Quantifies the environmental impact of building materials for whole building analysis and comparative design options.	Explores the environmental impact of different material choices and core-and-shell system options.
3	Cost	Free Software	Not free (requires Revit)	Free Software
4	Pros	Simple visualization of a project's potential and realized embodied carbon impacts.	Easy to use. Requires no special expertise. The result is on demand. Allows designers to evaluate various design options	Allows users to include energy simulation results to calculate operating energy effects alongside the effects of embodied energy
5	Cons	Works best in the design stage and construction stage only.	Interprets difficulty the LCA results	Technical knowledge of the building construction is required for data input.

**The information in the table is from each tool's technical documentation, which was based on the authors' insights gained from reviewing the developers' technical reports.*

Research Impact

The paper aims to analyze the current uses of LCA in construction, present LCA tools, compare applied tools in buildings, and explore three commonly used LCA tools for building studies. This study's results will assist project stakeholders in choosing the appropriate tools and selecting the most environmentally friendly products at different building life cycle stages (i.e., design, construction, and maintenance) for the project's success.

Research Methodology

Based on a literature review, the research studies LCA tools for quantifying buildings' environmental impact and provides a decision support framework for choosing LCA tools.

- Initially, data was gathered from a variety of sources, which identified research gaps and emerging trends in relevant LCA topics within the construction industry.
- Second, this extensive literature review attempted to answer the research questions raised above about the concept of LCA and discussed the similarities and differences between LCA tools.
- The study provided a basic knowledge of LCA tools and suggested eight criteria for the LCA analysis. These criteria were used as a filter in the decision support framework, which will assist stakeholders in deciding LCA tools for buildings.
- Lastly, the research applied the proposed criteria to compare three examples of digital LCA tools, including the Athena Impact Estimator, EC3, and Tally.
- The study delivered a roadmap for academic researchers who will continue analyzing and comparing LCA tools using the suggested methodology.

Criteria Proposal

- Each building has different characteristics that could influence the selection of appropriate LCA tools.
- By conducting a literature review of published studies and expanding upon the framework proposed by Dalla Mora et al. (2020), this research suggested eight criteria regarding the LCA analysis, as shown in Table 2.
- Selection criteria added a filter for study characteristics that helped determine whether they should be included, allowing researchers to better analyze the data.
- These criteria served as the attributes in the decision support framework, which thereafter will support stakeholders in making transparent decisions on selecting LCA tools in a construction project.

Design Stage | Development Level | Integration Tools | Impact Category | Learning Curve | Database | LCA Phase | Reporting Results

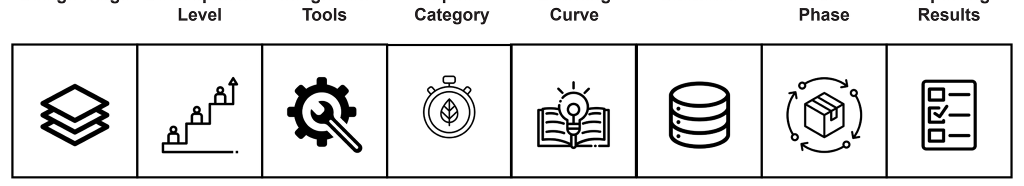

Table 2.
Analysis Criteria for choosing LCA tools

	Propose the Criteria in literature review of related topic	Al-Ghamdi & Bilec (2016)	Ansah et al. (2021)	Antón (2013)	Battisti et al. (2019)	Bueno & Fabricio (2016)	Chau et al. (2015)	Dalla Mora et al. (2020)	Han & Srebric (2011)	Lopes Silva et al. (2019)	Jrade & Abdulla (2012)	Rossi et al. (2012)	Singh et al. (2011)	Silva et al. (2009)	Srinivasan et al. (2014)	Ormazabal et al. (2014)
1	Design Stage	✓		✓	✓	✓	✓	✓			✓	✓			✓	
2	Level of Development	✓	✓			✓		✓	✓					✓	✓	
3	Integration Tools	✓	✓			✓	✓	✓	✓	✓	✓			✓		✓
4	Impact Category	✓	✓		✓	✓	✓		✓	✓	✓	✓	✓			✓
5	Learning Curve	✓	✓	✓	✓	✓		✓	✓	✓	✓			✓		✓
6	Database	✓	✓	✓	✓	✓		✓		✓		✓	✓			✓
7	LCA Phase	✓	✓				✓				✓	✓				
8	Reporting Results	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Summary	8	7	4	5	7	5	6	5	5	6	5	3	4	3	5

*The number of ticks for each LCA publication shows their contributions in terms of the study's proposed criteria

Table 3.
Comparison of selected LCA Tools based on the proposed Criteria

#	Analysis Criteria	EC3 tool (Embodied Carbon)	Tally (App in Revit)	Athena Impact Estimator
1	Design Stage	Construction documents. Bidding. Construction admin.	Schematic design. Design development. Construction documents.	Schematic design, Design development, Construction documents, Bidding & Construction admin.
2	Level of Development	The EC3 tool uses third-party verified EPD entries. The number of product categories have limited. Provide inaccurate estimates for materials.	Updates annually. Develops new features. Mapping from Revit elements. Need to model design options in Revit software.	Updates data annually. Not provide new features or user interface. Develops alternatives of material or assembly options.
3	Integration Tools	Integrates with Revit, Excel, etc. Automatically takeoffs from Revit model Use generic product category EPD (before products are specified)	Integrates with EC3 tool to compare manufacturer specific EPDs. No spreadsheet import of material quantities.	No Revit/BIM plugin is available Manual takeoffs from drawings and updating takeoffs Excel for importing material quantities.
4	Impact Category	Embodied Carbon for Global Warming Potential	Global Warming Potential Acidification Potential Eutrophication Potential Ozone Depletion Potential Smog Formation Potential Primary Energy Demand Non-renewable Energy	Global Warming Acidification Human Health Respiratory Effects Ozone Depletion Photochemical Smog Eutrophication Fossil Fuel Consumption
5	Learning curve	Users can quickly provide owners with the information they need to set embodied carbon performance targets.	Easy to learn mapping functionality. Requires Revit knowledge Define relationships between BIM elements and construction materials from the Tally database.	Easy to learn the basics Extensive help file documentation. Customize the model of assemblies and envelope Provides flexibility for design options .
6	Database	Bases on EPD data. Data entry without BIM import is heavy. Materials must be entered by weight and volume, not length or surface area.	Relies on GaBi background Mostly industry average data manufacturer specific EPD Has no regionalization data assumptions for the U.S.	Relies on Ecoinvent background. Mostly industry average data. Limited manufacturer data. Regionalized assumptions for Canadian and the U.S.
7	LCA Phase	Production	Production, Construction, Use & End of life	Production, Construction, Use & End of life
8	Reporting Results	Enables the visualization of a project's potential. Realizes embodied carbon impacts. Understand the baselines. Sets reduction targets. Provides several carbon benchmarks for a project on the same design.	Provides detailed report generated for LEED submission, which includes graphs and an excel sheet. Has a detailed estimation of material quantities. Challenging to model option material/ assembly options .	Generates LEED results reports with basic graphs and Excel exports. Results are aggregated by element and cannot be disaggregated to show the contribution of individual materials or assemblies.

*EPD - Environmental Product Declarations; *LEED - Leadership in Energy and Environmental Design.
The data information is collected to identify these technologies based on the authors' insights gained from reviewing the developers' technical reports and personal practice experiences.

Research Results

The framework proposed in our research advanced the prior works which developed by Dalla Mora et al. (2020) by adding the following three criteria: learning curve, integration, and reporting results. In addition, this research applied our proposed framework to compare the three most widely used LCA tools, including EC3, Tally, and Athena. This research benefits practitioners and researchers by providing a road map to continue analyzing and comparing different LCA tools (e.g., OneClick LCA, SimaPro, or BEES) using the proposed framework.

Important Findings - Conclusions

- This research contributes to the body of knowledge by examining LCA methodologies and developing the criteria for choosing appropriate LCA methods, including the design stage, level of development, integration tools, impact category, learning curve, database, LCA phase, and reporting results.
- Moreover, this research explored that managing the database is one of the most significant issues with current LCA tools. It suggests that building information modeling (BIM) and LCA integration is an approach that might facilitate and simplify data management for LCA analysis throughout all building life cycles recommendation.

References

-Al-Ghamdi, Sami G., and Melissa Bilec. 2016. "Green Building Rating Systems and Whole-Building Life Cycle Assessment: Comparative Study of the Existing Assessment Tools." Journal of Architectural Engineering.

- Ansah, Mark Kyeredey, Xi Chen, Hongxing Yang, Lin Lu, and Patrick T. I. Lam. 2021. "Developing an Automated BIM-Based Life Cycle Assessment Approach for Modularly Designed High-Rise Buildings." Environmental Impact Assessment Review.

- Antón, Laura Álvarez. 2013. "Integration of LCA and BIM Considering Early Building/Construction Design Stages."

- Battisti, Alessandra, Sandra G. L. Persiani, and Manuela Crespi. 2019. "Review and Mapping of Parameters for the Early Stage Design of Adaptive Building Technologies through Life Cycle Assessment Tools." Energies.

- Bueno, Cristiane, and Márcio Fabricio. 2016. "Application of Building Information Modelling (BIM) to Perform Life Cycle Assessment of Buildings." Pós. Revista Do Programa de Pós-Graduação Em Arquitetura e Urbanismo.

- Chau, C. K., T. M. Leung, and W. Y. Ng. 2015. "A Review on Life Cycle Assessment, Life Cycle Energy Assessment and Life Cycle Carbon Emissions Assessment on Buildings." Applied Energy.

- Dalla Mora, Tiziano, Erika Bolzonello, Carmine Cavalliere, and Fabio Peron. 2020. "Key Parameters Featuring BIM-LCA Integration in Buildings: A Practical Review of the Current Trends." Sustainability.

- Ormazabal, Marta, Carmen Jaca, and Rogério Puga-Leal. 2014. "Analysis and Comparison of Life Cycle Assessment and Carbon Footprint Software." Pp. 1521–30 in Advances in Intelligent Systems and Computing.

- Rossi, Barbara, Anne-Françoise Marique, Mauritz Glaumann, and Sigrid Reiter. 2012."Life-Cycle Assessment of Residential Buildings in Three Different European Locations, Basic Tool." Building and Environment.

- Silva, Vanessa, Natália Barros, and Regina Ruschel. 2019. "Building Information Modelling for Whole-Building LCA: BIM4LCA." IOP Conference Series: Earth and Environmental Science.

- Singh, Amanjeet, George Berghorn, Satish Joshi, and Matt Syal. 2011. "Review of Life-Cycle Assessment Applications in Building Construction." Journal of Architectural Engineering.

- Srinivasan, Ravi S., Wesley Ingwersen, Christian Trucco, Robert Ries, and Daniel Campbell. 2014. "Comparison of Energy-Based Indicators Used in Life Cycle Assessment Tools for Buildings." Building and Environment.

Updated 2/28/2023

Poster Title: *A Review of Life Cycle Assessment Tools for Measuring the Environmental Impact of Building and a Decision Support Framework for Choosing Among Them.*

Introduction/Problem Statement: *The increased environmental concerns in recent decades have resulted in examining waste emissions, resource utilization, and resource depletion. A holistic environmental assessment should consider all these factors. Researchers, policymakers, and companies are paying more attention to environmental management. As a result, organizations are developing their environmental practices to enhance environmental management throughout the building life cycle. Contemporary life cycle assessment (LCA) stands out as a reliable and comprehensive method that effectively communicates such benefits to stakeholders and offers them more leverage. LCA is increasingly being used to assess how construction processes affect the environment and minimize these impacts. There is a need for research on the use of LCA tools in buildings, which is a key point and a solution to facilitate environmental management practices and transform the construction industry.*

Research Objectives: *The paper aims to analyze the current uses of LCA in construction, present LCA tools, compare applied tools in buildings, and explore three commonly used LCA tools for building studies. This study's results will assist project stakeholders in choosing the appropriate tools and selecting the most environmentally friendly products at different building life cycle stages (i.e., design, construction, and maintenance) for the project's success.*

Research Methodology: *Based on a literature review, the research studies LCA tools for quantifying buildings' environmental impact and provides a decision support framework for choosing LCA tools. Initially, data was gathered from a variety of sources, which identified research gaps and emerging trends in relevant LCA topics within the construction industry. Second, this extensive literature review attempted to answer the research questions raised above about the concept of LCA and discussed the similarities and differences between LCA tools. The study provided a basic knowledge of LCA tools and suggested eight criteria for the LCA analysis. These criteria were used as a filter in the decision support framework, which will assist stakeholders in deciding LCA tools for buildings. Lastly, the research applied the proposed criteria to compare three examples of digital LCA tools, including the Athena Impact Estimator, EC3, and Tally. The study delivered a roadmap for academic researchers who will continue analyzing and comparing LCA tools using the suggested methodology.*

Preliminary or Final Results: *This research contributes to the body of knowledge by examining LCA methodologies and developing the criteria for choosing appropriate LCA methods, including the design stage, level of development, integration tools, impact category, learning curve, database, LCA phase, and reporting results. Moreover, this research explored that managing the database is one of the most significant issues with current LCA tools. It suggests that building information modeling (BIM) and LCA integration is an approach that might facilitate and simplify data management for LCA analysis throughout all building life cycles.*

Research Impact: *The framework proposed in our research advanced the prior works which developed by Dalla Mora et al. (2020) by adding the following three criteria: learning curve, integration, and reporting results. In addition, this research applied our proposed framework to compare the three most widely used LCA tools, including EC3, Tally, and Athena. This research benefits practitioners and researchers by providing a road map to continue analyzing and comparing different LCA tools (e.g., OneClick LCA, SimaPro, or BEES) using the proposed framework.*

Safety and Health Education in the Curricula of Construction-related Programs in Nigeria

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Similar to other injury-prone industries, the construction sector experiences an elevated number of accidents regularly. These inauspicious occurrences mostly lead to unwanted variability in project performance indicators and exert negative impacts on the victims, their families, and society. The major causes of accidents in the construction industry have often been linked to human factors, particularly the lack of adequate safety and health education in tertiary institutions. This study evaluates safety and health education in the curricula of construction-related programs in Nigeria. First, accredited construction-related programs in Nigerian universities were identified after which the curricula of 14 selected programs were examined to determine safety and health education provisions. Thereafter, a survey was designed and administered to faculty from six universities (one per geopolitical zones) to investigate their perception of the barriers and drivers to the inclusion of safety and health education in the curricula of construction-related programs. Findings from the study revealed the existing lack of construction safety and health education in the curricula and the main barriers/drivers impacting inclusion in Nigerian construction programs. These findings could be used to develop a framework and strategies for integrating construction safety and health education into the curricula of construction-related programs in Nigeria.

Keywords: Construction Safety and Health, Education Curriculum, Nigeria, Occupational Safety and Health, Tertiary Institution.

Introduction

The construction industry is undoubtedly the pillar of the economic and social growth of every nation because of its importance for infrastructural development. It serves as a strong nexus for all other sectors of the economy and serves as the pivot of national development. However, the construction industry has historically experienced a disproportionately high rate of disabling injuries and fatalities for its size when compared with other labor-intensive industries (Hinze, 1997; Shen et al., 2017). When fatal accidents occur on a construction site, they adversely impact the construction project in several ways, de-motivate workers, disrupt site activities, delay project progress, and affect the overall project cost, productivity, and reputation of the firms concerned (Okolie & Okoye, 2012). The direct and indirect costs of the high number of injuries, illnesses, and fatalities experienced in construction relative to other industries contribute to the cost of construction, making the safety of the construction workforce critical.

Construction worker safety is a continuous source of concern in most developing countries (Nnaji et al., 2017). Despite the increasing growth in the construction subsector in Nigeria, the institutional and regulatory framework for construction health and safety is highly fragmented and poorly implemented (Okolie & Okoye, 2012). The Nigerian construction industry is plagued with high injury and accident rates (Idoro, 2011). Although safety is perceived to be an important project indicator, the collective actions of stakeholders in the Nigerian construction industry invalidate this premise (Nnaji et al., 2017). Studies show that Nigerian construction workers are unaware of important health and safety practices (Diugwu et al., 2012; Olatunji et al., 2007) and organizations do not pay adequate attention to health and safety management (Diugwu et al., 2012). The lack of safety emphasis in the formal educational system has been identified as one reason for the lack of safety awareness among educated workers in the construction industry (Idubor & Oisamoje, 2013; Afolabi et al., 2016).

Health and safety training is universally acknowledged as means of limiting the costs associated with construction accidents (Burke et al., 2006). The elevated occupational injuries and illnesses reported annually in the construction industry across the world underpin the need to develop a superior understanding of the efficiency of safety and health education and training. According to Gambatese (2003), the education and training of project personnel in the area of safety are significant aspects of safe construction job sites. Higher education institutions bear a profound and moral responsibility to increase the awareness, knowledge, skills, and values needed to create a just and sustainable future (Cortese, 2003). After receiving formal education from a university, the involvement of the many workers that enter the construction industry in different capacities can have a considerable influence on construction site safety (Gambatese, 2003).

The incorporation of construction site safety in university curricula has been the topic of prior research. Higher education plays a critical role in preparing most of the professionals who develop, lead, manage, teach, work in, and influence society's institutions (Cortese, 2003). According to Burke et al. (2006), most training interventions positively influence safety knowledge, the adoption of safe work behaviors and practices, as well as occupational safety and health (OSH) outcomes. There is therefore a real need to examine if construction site safety is included and covered (and to what extent) in university-level education curricula, particularly in developing countries such as Nigeria faced with fundamental challenges related to lack of safety knowledge, awareness, and practices. Improvements in safety performance can be gained when project personnel is knowledgeable of the potential construction site hazards and the appropriate means to mitigate the hazards (Gambatese, 2003). Education imparts high-level knowledge and skills that are transferable to different situations (Haslam et al., 2005) and the effectiveness of safety training practices is an important part of safety management on a construction site (Awolusi et al., 2017). This research presents an appraisal of the construction health and safety education provisions in the curriculum of tertiary institutions in Nigeria by examining the content of the curricula of construction-related programs in Nigeria.

Literature Review

Researchers and stakeholders in the construction industry have been directing efforts with good progress toward improving safety performance in developed nations but developing nations appear to be lagging due to basic challenges such as a lack of safety education and awareness. This section reviews construction safety and health statistics, education, and training globally and in Nigeria.

Construction Safety and Health Statistics

The construction sector accounts for a very high rate of injuries and fatalities relative to other industrial sectors (Choudhry & Fang, 2008; Awolusi & Marks, 2017). In the U.S., construction contributes to 5% workforce, 6% of workplace injuries, and 21.2% of workplace fatalities (OSHA 2021). Data from the Bureau of Labor Statistics show that out of 4,764 worker fatalities in private industry in the year 2020, 1008 were recorded in construction with an injury rate of 10.2 per 100,000 employed workers (BSL, 2021). The leading causes of worker deaths in the construction industry (falls, struck-by-object, electrocution, and caught-in/between) were responsible for more than half (65.9%) of the construction worker deaths in 2020 (CPWR, 2022). In the same year, the construction industry experienced 174,000 non-fatal occupational injuries and illnesses at a rate of 3.2 per 100 full-time workers (BSL, 2021). About 15% of workers' compensation costs are spent on workers injured at a construction site. Each year, around 80,000 construction workers in the UK suffer from an illness they believe was caused or made worse by their work (HSE, 2017). Hong Kong is also well-known for its elevated construction accident rates recording a total of 3,860 occupational injuries in 2016 (HKOSH, 2016). Even with the drop in the accident rate, construction still accounts for 11 % of workplace accidents in Hong Kong.

This situation is worse in developing countries, particularly Nigeria where there are no reliable sources of data for such accident records (Okolie & Okoye, 2012). According to the occupational health and safety profile developed by the Federal Ministry of Labour and Employment in collaboration with the International Labour Organization, Nigeria recorded a total number of 3461 occupational accidents/injuries and 238 fatalities across different sectors of the economy between 2014 and 2016. The construction industry reported the highest number of work-related accidents/injuries, accounting for over 39% of the total figures (ILO, 2016). Africa is faced with inconsistencies and subjectivity in the reported safety data of certain groups of workers, the poor determination of occupational disease, and the impacts of some legal and bureaucratic features of the reporting systems (Loewenson, 1999). Although Nigeria is relatively experiencing a strong growth in construction activities, it is unfortunate to note that the enforcement of health and safety regulations is not a mainstream activity in the country (Okolie & Okoye, 2012). Due to employers' perceptions that the high number of accident reports may subject them to punitive measures from the enforcement authorities, underreporting of accidents in Nigeria appears high when compared to the actual number of accident reports (ILO, 2016). These situations indicate that the current structure for the regulation and enforcement of occupational safety and health in the Nigerian construction industry is inadequate.

Occupational Safety and Health in the Nigerian Construction Industry

As the most populous country in Africa and the 14th largest in land mass with a huge amount of natural and human resources, Nigeria should undoubtedly be categorized as a nation with very active industrial sectors. When compared with other subsectors of the Nigerian economy, the construction industry ranked 7th in the contribution to Gross Domestic Product (GDP) in 2015 despite being separated from the real estate sector (Okoye, 2016). According to data from the National Bureau of Statistics in Nigeria, the construction sector grew by 19.25% in nominal terms (year on year) in the fourth quarter of 2017 with an annual contribution of 3.77% in 2017 and 3.55% in 2016 (NBS, 2018). Despite recent efforts to improve site safety, the construction still accounts for an elevated number of occupational-related fatalities and the safety record continues to be one of the poorest, thus, hindering performance improvement (Alkilani et al., 2013; Shen et al., 2017). Although workplaces in some countries like the US and UK have become safer over the years due to efforts from researchers and stakeholders, a similar feat has not been achieved in Nigeria. Abubakar (2015) suggests that Nigeria and other developing countries could gain from the vast experiences of countries that have hugely invested and developed OSH management systems over several decades of hard work.

The hazardous nature of sectors such as the construction industry makes it unacceptable to undermine the importance of occupational safety and health in the Nigerian industrial sectors. Virtually all the occupational safety and health regulations used in Nigeria emanated from foreign countries (Tanko & Anigbogu, 2012). Major legislation that has been enacted to provide for the safety and health of the workforce in Nigeria include the Factories Act, CAP F1, Laws of the Federation of Nigeria (LFN), 2004; Employees" Compensation Act, 2010; Nigerian Minerals and Mining Act, 2007; and Nigerian Nuclear Safety and Radiation Act, 1995. Most SMEs and OSH practitioners in Nigeria have been relying on the Factories Act in the implementation of OSH workplace arrangements in their respective organizations and practices (ILO, 2016). In Nigeria, there is no national Occupational Safety and Health Board in place and no formal National OSH Management Systems have been developed by OSH authorities at the moment, but the country adopts the ILO – OSH 2001 as a guide (ILO, 2016). These regulations used in Nigeria do not efficiently capture construction health and safety nor encourage the need for safety and health education and training in educational institutions.

Construction Safety and Health Education and Training

University graduates hired to work in the construction industry typically have a degree in construction management, building science, civil engineering, or other related fields of study (Gambatese, 2003; Awolusi et al., 2022). These university graduates who are professionally qualified and educated workers are expected to handle different aspects of a construction project from inception to completion. One critical aspect is the design for safety concept (or prevention through design) which helps prevent workers' injuries by building safety into the design of construction projects and facilities. Designers and engineers of construction projects and facilities should be empowered to contribute to construction health and safety (Smallwood, 2020). According to a study by Gambatese (2003), construction programs address safety in the curricula more than civil engineering programs due to the accreditation requirements for construction programs. In the UK, construction worker safety is integrated at relevant points throughout the undergraduate civil engineering curriculum by most universities rather than addressing it in a separate course. Coverage of safety in this manner is due to the Joint Board of Moderators guidelines for developing degree programs and strengthened by the legislatively mandated Construction (Design and Management) Regulations in force throughout the U.K. which include the designer in the safety effort (HSE, 2015). The teaching of construction safety has become a firm requirement because of the need for graduating engineers to understand and implement the CDM Regulations (Gambatese, 2003). For engineers to effectively contribute to worker safety, they must possess at least a limited degree of expertise in construction safety. Without an understanding of safety standards and management, it would be difficult for designers to contribute to worker safety (Toole, 2005). In Canada, the inclusion of safety and health into engineering program curricula is made compulsory by the organization that accredits university-level engineering programs within Canada (Gambatese, 2003). A descriptive survey conducted among architectural departments at a university in South Africa revealed that architectural programs address construction health and safety (H&S) to a limited extent and that construction H&S is perceived to be fairly important to the discipline of architecture, and design-related activities have a moderate impact on construction H&S (Smallwood, 2020). The simplest way to make designers receive safety training might be to include it in the undergraduate engineering and architecture curriculum (Toole, 2005).

In Nigeria, it is not clear if there is a firm accreditation requirement for construction-related programs to include safety and health in their curricula. However, the Department of Environmental Health Services at the University of Ibadan and the Centre for Occupational Health, Safety and Environment at the University of Port Harcourt currently offer master's and doctoral degrees in “Safety, Health, and Environment” and “Occupational Health, Safety, and Environment”, respectively (ILO 2016). Although, these programs are primarily tailored to meet the needs of industrial workers who are in the health, safety, and environment (HSE) departments, and other related departments, more structured curricula would be needed to take care of the uniqueness of different high-risk industrial sectors such as construction.

Research Method

First, a publicly available database of the National Universities Commission (NUC) was probed to obtain the list of all accredited universities in Nigeria, and extract the list of universities with construction-related programs (including Building, Civil Engineering, Architecture, and Quantity Surveying). Thereafter, 14 construction-related programs from 14 universities were carefully selected across the six geopolitical zones (i.e., South West, South South, South East, North Central, North West, and North East) in Nigeria using a stratified sampling technique. Another online search was conducted to obtain the catalog or handbook of these programs. Furthermore, a content analysis was conducted to examine the safety and health education provisions in the curricula of these programs. The programs considered for the content analysis were only Building and Civil Engineering because the graduates from these programs are common among those that end up taking up a role as a project and construction engineer, supervisor, or manager to oversee the effective operations of workers and other resources on construction sites. Each curriculum is often prepared by the curriculum team in each university in line with the template and guidance of the NUC.

Furthermore, a literature review was conducted to identify the barriers and drivers to the inclusion of safety and health education in the curricula of construction-related programs. Thereafter, a structured survey was designed using the identified barriers/drivers and administered (using both online and in-person distribution) to faculty in six universities (one per geopolitical zones) to investigate their perception of the barriers and drivers to the inclusion of safety and health education in the curricula of construction-related programs. A section of the survey was designed to collect demographic information of the respondents while two other sections were dedicated to collecting the faculty’s perception of the barriers and drivers. The level of agreement of the faculty with the barriers and drivers was measured using a five-point Likert scale (1 - strongly disagree to 5 - strongly agree). A total of 112 complete responses were obtained from the surveys administered and the collected data were analyzed using mean item scores (MIS) run on IBM SPSS Statistics.

Results and Discussion

This section presents the results of the analysis carried out in the study. Data analysis shows that there are 192 universities in Nigeria out of which 44 (23%) are Federal, 49 (26%) are State, and 99 (52%) are Private universities indicating that there is a huge interest from the private sector in education in Nigeria. Only about 31 (16%) of these universities have construction-related programs including (Building, Civil, Engineering, Architecture, and Quantity Surveying). Data also show that 15 (48%) of these universities are Federal, while 9 (29%) and 7 (23%) are State and Private universities, respectively, indicating that most construction-related programs can be found in Federal universities. The analysis also shows that construction-related programs are offered by some of the oldest universities in the country indicating a high tendency for the presence of appropriate support for construction-related education. Figure 1 shows that there is a total of 102 construction-related programs spread across 31 universities in Nigeria. Approximately 29% (30) of these programs are in Civil Engineering, 27% (28) in Architecture, and 22% (22) each are in Building and Quantity

Surveying. This is not surprising since Civil Engineering is the oldest engineering discipline after Military engineering, while Architecture is one of the oldest and most important areas of art. The distribution of the programs across the different geopolitical zones also shows that most of the construction-related programs (39%) are in the southwestern region of Nigeria.

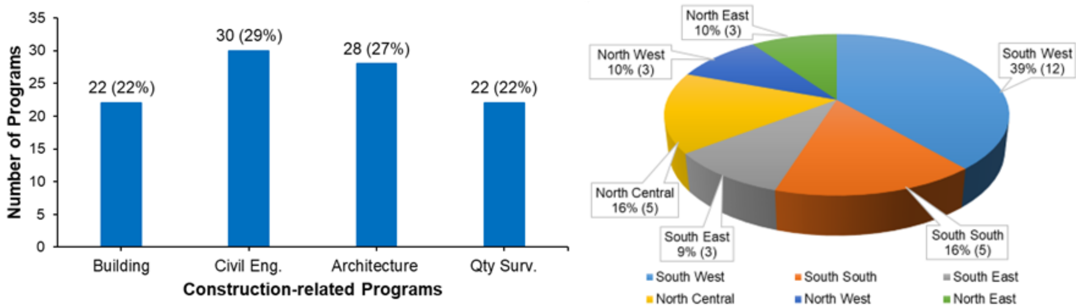

Figure 1: Number of Construction-related programs in Nigeria by (a) Program Type (b) Geopolitical region

Construction Safety and Health Education in the Nigerian Universities

The content analysis of the curricula shows that only one out of the 14 programs (Building and Civil Engineering) examined had a course on construction health and safety in its curriculum. The topics taught in this safety and health course include "Introduction to health and safety on construction sites", "Health and safety regulations", "Use of personal protective equipment (PPE)", "Case studies on construction sites in relation to health and safety practices", "Safety measures on plants and equipment, and general site conduct." This result indicates that graduates of Building and Civil Engineering programs from the selected universities may not possess the required knowledge of construction health and safety. The implication of this finding is evident in the high number of injuries and accidents constantly reported in the Nigerian construction sector. This finding is in tandem with previous studies on the lack of construction health and safety education awareness among educated workers in the construction industry in Nigeria (Idubor & Oisamoje, 2013; Afolabi et al., 2016).

Barriers and Drivers to Safety and Health Education Inclusion in Construction Programs' Curricula

The demographic distribution of the faculty that responded to the survey indicates that 47.3% of the respondents were from Building, 20.5% from Civil Engineering, 17.0% from Architecture, and 15.2% from Quantity Surveying, confirming the assumption about the most common graduate students that take up a role as a project and construction engineer, supervisor, or manager in the construction industry. While 72.0% of the faculty hold a Ph.D. degree, 27.7% hold a master's degree, and 65.2% of the faculty surveyed have more than 10 years (with an average of 25 years) of teaching experience.

The analysis of the faculty's perception of the barriers to the inclusion of safety and health education in the curricula of construction programs in Nigeria shows the lack of enforceable safety and health standards and regulation as the major barrier which is a leadership or government-related factor (Table 1). The next three were industry-related barriers including not considering safety a project performance indicator, lack of awareness of safety and health in the construction industry, and lack of support from professional organizations such as the Nigerian Institute of Building (NIOB), Nigerian Society of Engineers (NSE), Nigerian Institute of Quantity Surveyors (NIQS) and Nigerian Institute of Architects (NIA). On the other hand, the institutional or university-related barriers were not considered major barriers by the faculty. The findings show that more work needs to be put in place at the industry level to help combat the obstacles facing the inclusion of safety and health education into the curricula of construction programs in Nigeria.

Table 1
Barriers to the inclusion of construction safety and health education in Nigerian curricula

Factor	Barriers	MIS	Rank
B1	Lack of enforceable safety and health standards and regulation.	3.86	1
B2	Worker safety and health is currently not considered one of the important performance indicators (like cost, schedule, and quality)	3.60	2
B3	Lack of awareness of safety and health in the construction industry	3.48	3
B4	Lack of support from professional organizations	3.45	4
B5	No regulation supporting or mandating safety and health education for construction professionals	3.29	5
B6	Lack of respect for human rights	3.23	6
B7	Safety and health course not required by the accreditation agency	3.10	7
B8	Poor level of research and development	2.92	8
B9	Lack of adequate teaching facilities	2.50	9
B10	Lack of lecturers/professors knowledgeable in safety and health	2.46	10
B11	Lack of adequate teaching materials	2.21	11

Table 2 also shows that the faculty consider all the factors as drivers with the mean item score (MIS) ranging from 3.73 to 4.34. In line with their perception of the major barriers, the faculty believe that the presence of enforceable safety and health standards and regulations, making safety and health course a requirement for accreditation, promoting the level of research and development, and considering safety and health as one of the important performance indicators could help promote the inclusion of safety and health education into the curricula of construction programs in Nigeria. These findings indicate that a concerted effort of the government, industry, and university stakeholders is required to effectively drive or foster the inclusion of safety and health education into the curricula of construction programs.

Table 2
Drivers of the inclusion of construction safety and health education in Nigerian curricula

Factor	Drivers	MIS	Rank
D1	Presence of enforceable safety and health standards and regulations	4.34	1
D2	Making a safety and health course a requirement for accreditation	4.29	2
D3	Promoting the level of research and development	4.21	3
D4	Considering worker safety and health one of the important performance indicators (like cost, schedule, and quality)	4.18	4
D5	Presence of lecturers/professors knowledgeable in safety and health	4.16	5
D6	Passing a regulation mandating safety and health education for construction professionals	4.15	6
D7	Presence of support from professional organizations	4.14	7
D8	Promoting respect for human rights	4.13	8
D9	Presence of adequate teaching materials	4.08	9
D10	Promoting awareness of safety and health in the construction industry	4.04	10
D11	Presence of adequate lecture facilities	3.73	11

Conclusion

Despite the urgent need to reduce the rates of injuries, illnesses, and fatalities on construction sites, safety and health education has not been made a priority in construction-related programs in Nigeria. It is disheartening to note that adequate provisions have not been made for safety and health education in the curricula of construction-related programs in Nigeria. Indeed, it seems like the graduates coming out of these institutions can only lead the construction industry down the current unhealthy, inequitable, and unsustainable path. A firm understanding of the needs including barriers, drivers, benefits, and how best to incorporate worker safety and health education into the curricula of the programs is a critical public need considering the incessant accidents experienced on construction sites across the world, particularly in Africa where some of these incidents go unreported.

This study contributes to knowledge by drawing out the major barriers and drivers to the inclusion of safety and health education in the curricula of construction programs in Nigeria and laying a strong foundation for future studies and investigations. It is however incumbent on stakeholders including professionals in the construction industry, educators and researchers in academia, and government (regulatory) agencies to explore the importance of safety and health education in combatting the menace facing the construction industry. Current research work being undertaken in this field includes engaging the stakeholders in the industry, academia, and government to evaluate the barriers, drivers, and potential benefits to develop an effective framework and strategies for the integration and promotion of safety and health education in construction programs in Nigeria.

References

Abubakar, U. (2015). An Overview of the Occupational Safety and Health Systems of Nigeria, UK, USA, Australia and China: Nigeria Being the Reference Case Study. *American Journal of Educational Research*, 3(11), 1350-1358.

Afolabi, A. O., Tunji-Olayeni, P. F., Amusan, L. M., Omuh, I. O., Ojelabi, R. A., & Oyeyipo, O (2016). Safety Cultured Industry through the Integration of Occupational Health and Safety (OHS) Courses in the Built Environment Curriculum. *Proceedings of "INTED2016 Conference" 7th-9th March 2016, Valencia, Spain.*

Alkilani, S. Z., Jupp, J., & Sawhney, A. (2013). Issues of Construction Health and Safety in Developing Countries: A Case of Jordan. *Australasian Journal of Construction Economics and Building*, 13(3), 141-156.

Awolusi, I. G. & Marks, E. D. (2017). Safety Activity Analysis Framework to Evaluate Safety Performance in Construction." *Journal of Construction Engineering and Management*. 143(3), 05016022-1-12

Awolusi, I., Marks, E., & Vereen, S. (2017). Qualifications and Staffing Requirements of Safety Personnel in Construction. *Practice Periodical on Structural Design and Construction*, 22(4), 04017009-1-8.

Awolusi, I., Sulbaran, T., Song, S., Nnaji, C., & Ostadalimakhmalbaf, M. (2022). Safety Education in the Curriculum of Construction Programs. *In the 9th International Conference on Construction Engineering and Project Management* (pp 508-51).

Bureau of Labor Statistics (BLS). (2021). Census of fatal occupational injuries (CFOI)—Current and revised data 2020 chart package. https://www.bls.gov/iif/oshwc/cfoi/cfch0015.pdf

Burke, M. J., Sarpy, S. A., Smith-Crowe, K., Chan-Serafin, S., Salvador, R. O., & Islam, G. (2006). Relative effectiveness of worker safety and health training methods. *American Journal of Public Health*, 96(2), 315–324.

Choudhry, R. M., & Fang, D. (2008). Why operatives engage in unsafe work behavior: Investigating factors on construction sites. Safety Science, 46(4), 566–584.

Cortese, A. D. (2003). The critical role of higher education in creating a sustainable future. *Planning for Higher Education*, 31(3), 15–22.

Diugwu, I. A., Baba, D. L., & Egila, A. E. (2012) Effective regulation and level of awareness: An expose of the Nigeria's construction industry. *Open Journal of Safety Science and Technology*, 2, 140-146
Gambatese, J. (2003). Safety Emphasis in University Engineering and Construction Programs. *Continuing Education*, (September), 1–18.
Haslam, R. A., Hide, S. A., Gibb, A. G., Gyi, D. E., Pavitt, T., Atkinson, S., & Duff, A. R. (2005). Contributing factors in construction accidents. *Applied ergonomics*, *36*(4), 401-415.
Health and Safety Executive (HSE). (2015). Managing health and safety in construction: - Construction (Design and Management) Regulations 2015: Guidance on Regulations. *Health and Safety Executive.*
Health and Safety Executive (HSE). (2017). Health and safety in construction in Great Britain, 2017. *Health and Safety Executive.*
Hinze, J. W. (1997). *Construction Safety*. Prentice Hall, Upper Saddle River, New Jersey.
Hong Kong Occupational Safety and Health (HKOSH). (2016). Occupational Safety and Health Statistics 2016. *Labor Department, The Government of the Hong Kong Special Administrative Region*. http://www.labour.gov.hk/eng/osh/pdf/OSH_Statistics_2016_NEW_EN.pdf
Idoro, G. I (2011). Comparing occupational health and safety (OHS) management efforts and performance of Nigerian construction contractors. *Journal of Construction in developing Countries*, 16(2), 151-173.
Idubor, E. E., & Oisamoje, M. D (2013). An Exploration of Health and Safety Management Issues in Nigeria's Effort to Industrialize. *European Scientific Journal*, 9 (12).
International Labour Organization (ILO). (2016). Nigeria Country Profile on Occupational Safety and Health 2016. *International Labour Organization*, http://www.ilo.org/wcmsp5/groups/public/---africa/---ro-addis_ababa/---ilo-abuja/documents/publication/wcms_552748.pdf
Loewenson, R. (1999). Assessment of the Health Impact of Occupational Risk in Africa: Current Situation and Methodological Issues. *Epidemiology*, 10(5) 632-639.
National Bureau of Statistics (NBS). (2018). Nigerian Gross Domestic Product Report. *National Bureau of Statistics*, https://www.proshareng.com/admin/upload/reports/10988-UNITEDCAPITALPLCFINANCIALSTATEMENTSFEBRUARY2018-proshare.pdf
Nnaji, C., Gambatese, J., Awolusi, I., & Oyeyipo, O. (2017, June). Construction safety innovation awareness and adoption in Nigeria: A mixed method approach. In *Joint CIB W099 and TG59 International Construction Conference* (pp. 361-372).
Occupational Safety and Health Administration (OSHA). (2021). Commonly used statistics. *U.S. Bureau of Labor Statistics*, http://www.osha.gov/oshstats/commonstats.html
Okolie, K. C., & Okoye, P. U. (2012). Assessment of National Culture dimensions and construction health and safety Climate in Nigeria. *Science Journal and Environmental Engineering Research*, 1–6. https://doi.org/10.7237/sjeer/167
Okoye, P. U. (2016). Improving the Safety Performance of Nigeria Construction Workers : A Social Ecological Approach. *Universal Journal of Engineering Science*, 4(2), 22–37.
Olatunji, O. A., Aje, O. I., & Odugboye, F. (2007). Evaluating Health and Safety Performance of Nigerian Construction Site. *In Rotterdam, Netherlands: CIB World Building Congress*, 1176-1190.
Shen, X., Awolusi, I., & Marks, E. (2017). Construction Equipment Operator Physiological Data Assessment and Tracking. *Practice Periodical on Structural Design and Construction*, 22(4), 04017006-1-7.
Smallwood, J. (2020). The need for the inclusion of construction health and safety (H&S) in architectural education. In *Sustainable Ecological Engineering Design* (pp. 179-190)
Tanko, B. L., & Anigbogu, N. A. (2012). The use of personal protective equipment (PPE) on construction sites in Nigeria. In *Proceedings of the 4th West Africa Built Environment Research (WABER) Conference* (pp. 1341-1348).
Toole, T. M. (2005). Increasing Engineers' Role in Construction Safety: Opportunities and Barriers. *Journal of Professional Issues in Engineering Education and Practice*, 131(3), 199–207.

Prevalence of Fatigue Among Construction Workers in The United States

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Within dynamic and complex construction environments, fatal and non-fatal occupational records are alarming all over the world. Fatigue among workers is one of the key causes which affects their ability to operate safely. To improve safety management, the prevalence of fatigue among workers must be investigated to implement effective interventions for fatigue mitigation. However, the prevalence of fatigue among construction workers in the United States has not been studied. Therefore, this research explores this gap by recruiting 120 workers in the U.S. To achieve the research goals, the worker's level of fatigue (i.e., acute, chronic, and inteshift recovery) was measured using a validated OFER scale. Data analysis revealed (1) the prevalence of fatigue among construction workers is alarming (OFER Score=34.23), that acute fatigue, among all aspects of it, has the most profound impact on workers, and (2) there are no statistical correlations between measured fatigue levels and age and experience of construction workers. The findings of this study will be beneficial to practitioners and researchers in construction to implement effective safety measures to prevent accidents in workplaces.

Key Words: Fatigue, Construction Workers, Construction Safety, OFER Scale

Introduction

The construction industry is known for a dynamic and complex process with unique projects that have created various challenges for workers. These challenges have consistently led to a high rate of fatal and non-fatal injuries. In 2018, 20% of work-related mortalities were related to the construction industry in the European Union, the highest number of other industries (Namian et al. 2021). In the first three-quarters of that time, the construction accounts for 673 mortalities in 581 safety accidents that occurred in China (Xing et al. 2020). Similarly, in the United States, whereas only 4 % of the U.S. workforce is employed in construction, 20% of work-related mortalities are related to this industry (Al-Bayati 2022). Unfortunately, in 2019, approximately 15 workers died every day from catastrophic accidents, which shows an over 40% increase since 2007 in the United States (Ibrahim et al. 2022; Namian et al. 2022a).

It has been determined that the main factors of happening these accidents can be found human errors, unsafe behavior, a lack of knowledge and safety training, and poor and ineffective management at the sites (Abukhashabah et al. 2019; Bussier and Chong 2022; Namian et al. 2022b). One of the accident prevention methods is identifying, evaluating, and controlling potential dangers (Christian et al. 2009). This is because when accidents occur frequently, workers tend to ignore environmental hazards or believe they are not important enough to address, which prevents them from taking any corrective action to eliminate or control them.

Researchers have attempted to identify different variables that can exert an impact on workers' safety performance. For example, some demographic characteristics such as age, gender, training, experience, job role, and education have been determined to have a profound impact on workers' situational awareness (Ibrahim et al. 2022). More recently, some researchers have identified some variables like safety attitude (Kashmiri et al. 2020), safety climate (Pandit et al. 2019), safety training (Namian et al. 2016), distraction (Namian et al. 2018), and superstitious beliefs (Namian et al. 2020) that affect workers' safety performance.

One of the main factors identified globally as a harmful variable on safety performance is attributed to fatigue. A recent study has shown a strong negative correlation between fatigue and two essential components of safety (Hazard Recognition and Safety Risk Perception). In this study, Fewer hazards and lower safety risks were recognized and perceived by workers who have a higher fatigue level (Namian et al. 2021). Moreover, it has been identified as a main contributing factor to approximately 50% to work accidents (Sari et al. 2021). This illustrates how the fatigue factor is vital when it comes to managing Jobsite injuries. However, there is a dearth of research on the prevalence of fatigue among construction workers to help practitioners and researchers with fatigue mitigation. Therefore, this article aims to investigate this gap of knowledge in the United States.

Research Method

Fatigue is a pervasive and serious problem for workers around the world in different industries. For example, in the transportation industry is estimated that fatigue accounts for between 15 and 20 of all accidents (Bendak and Rashid 2020). In the construction industry, the impacts of worker fatigue can be more dangerous to occupational health and safety than in other industries caused of the temporary nature of construction sites (Xing et al. 2020). In the United States, work-related fatigue and overexertion are responsible for more than 30% of all occupational accidents (Yu et al. 2019). Moreover, it is estimated that the U. S. employers cost $136 billion annually for fatigue-related lost productivity in the world (Xu and Hall 2021).

Given the importance of fatigue on workers' safety, researchers have attempted to measure the prevalence of fatigue on job sites globally. Fatigue in some countries like Canada, Japan, the E.U., and Sweden has been reported to be a high prevalence (Lu et al. 2017). Generally, the prevalence of fatigue in the workplace between almost 10% and 40% has been reported (Bhuanantanondh et al. 2021). Understanding the prevalence of fatigue is known as the first step to taking effective actions for improving safety (Lu et al. 2017). Therefore, the present study aims to investigate the prevalence of fatigue among construction workers in the United States. To achieve the research goal, workers were selected randomly for active construction projects in the U. S. and asked to participate in the study. The details pertaining to the participants and fatigue level evaluation are explained in the following sections.

Participants

To measure the research objective, data were gathered from some active projects in the United States. Almost 50% of data was gathered from North Carolina State (32.50%) and Georgia State (11.67%). Over a period of one month in 2019, 120 construction workers were recruited randomly to answer the questions in person using a questionnaire. Workers' participation was voluntary, and the researchers assured that the information collected was confidential and would not be used for other purposes except for statistical use. Information will also not be given to employers or supervisors. On average, Participants' age and their job experience were from 18 to 67 (age average= 37.63) and 0 to 45 (experience average= 13.95), respectively. Only 7.5% (n=120) of the participants mentioned that they had had injuries in the past 12 months, and over 45% of workers have an OSHA 10 / OSHA 30 Certification.

Fatigue Level Evaluation

Work-related fatigue has an adverse effect on the productivity and performance of workers. Past research has demonstrated that fatigue can reduce the quality of work and productivity and increase safety problems and human errors in the workplace (Xu and Hall 2021). In the construction industry, heavy workload, awkward working posture, and prolonged working hours have been reported as contributing factors to workers' fatigue, leading to reduced decision-making ability, reduced motivation and attention, reduced response to changes or increased reaction time for thinking, and increased distraction (Xing et al. 2020; Zhang et al. 2015). In 2014, 40% of fall accidents were attributed to workers' fatigue (Parijat and Lockhart 2008).

To measure fatigue in construction, researchers have tried to utilize emerging technologies to detect the fatigue level of workers accurately. For example, surface electromyographic (sEMG) is attached directly to the skin of workers to measure muscle fatigue, and a wearable electroencephalogram (EEG) sensor can be used for psychosocial conditions to measure mental fatigue of workers (Li et al. 2019; Yu et al. 2019). Although these new technologies are promising, the inability of worker's normal work and cost issues are major hindrances. Therefore, fatigue monitoring in the construction industry has depended on self-report information.

Fatigue is divided into two acute and chronic types based on time (long-term and short-term). Acute fatigue is a common phenomenon related to short-time mental or physical heavy activities that usually are resolved by compensatory mechanisms (Aratake et al. 2007). Chronic fatigue is created if acute fatigue continues, and it reduces an individual's corporeal and physical abilities. Many researchers have stated that chronic fatigue is the reason for the most dangerous events in working (Rajaratnam and Arendt 2001). To accurately measure workers' fatigue levels in each project, information collected all week day's (except holidays) and workers' all efficient hours presently, using the Occupational Fatigue Exhaustion Recovery scale (OFER) (Winwood et al. 2005). OFER-15 questionnaire includes three dimensions: chronic fatigue (C.F.) (five items), acute fatigue (A.F.) (five items), and recovery between work shifts (5-items). The criterion of response in this questionnaire is a 7-point Likert scale (1 = strongly disagree, 2 = disagree, 3 = somewhat disagree, 4 = neither agree nor disagree, 5 = somewhat agree, 6 = agree, 7 = strongly agree). Table 1 shows three questions of the OFER-15 scale, which was used to measure workers' fatigue levels. Accountable quantities for each item under the criterion are achieved between 0 to 35, and more distinction of each of these criteria will show more intensity of that. This questionnaire is the first instrument that can distinguish acute and chronic fatigue from each other.

Table 1

Three sample questions of the OFER Scale (Winwood et al. 2005)

Fatigue	**Numbers**	**Questions**
Chronic Fatigue	1	"I often feel I'm 'at the end of my rope' with my work"
Acute Fatigue	6	"After a work shift, I have little energy left"
Intershift Recovery	11	"I never have enough time between shifts to recover my energy completely"

Result and Discussion

The data collected from the 120 interviewed construction workers were gathered and statistically analyzed. Firstly, the descriptive statistics of the participants' fatigue levels and the frequency distribution of the subscale intensity of the OFER questionnaire are presented in Tables 2 and 3 and Figure.1.

Table 2

Descriptive statistics of fatigue levels

Scale	**Minimum**	**Maximum**	**Mean**	**Median**	**SD**
Occupational Fatigue Exhaustion Recovery (OFER)	3	81	34.23	33	18.23
Subscale					
Chronic	0	30	10.13	8	7.57
Acute	2	27	13.27	13	6.59
Intershift recovery	0	30	10.84	10	6.44

Table 3

The frequency distribution of the subscale intensity of the OFER questionnaire (n=120)

Subscale	**Intensity**			
	Low	Low/Moderate	Moderate/High	High
Chronic	44 (36.67%)	20 (16.67%)	27 (22.50%)	29 (24.17)
Acute	2 (1.67%)	33 (27.50%)	28 (23.33%)	57 (47.50%)
Intershift Recovery	3 (2.50%)	64 (53.33%)	25 (20.83%)	28 (23.33%)

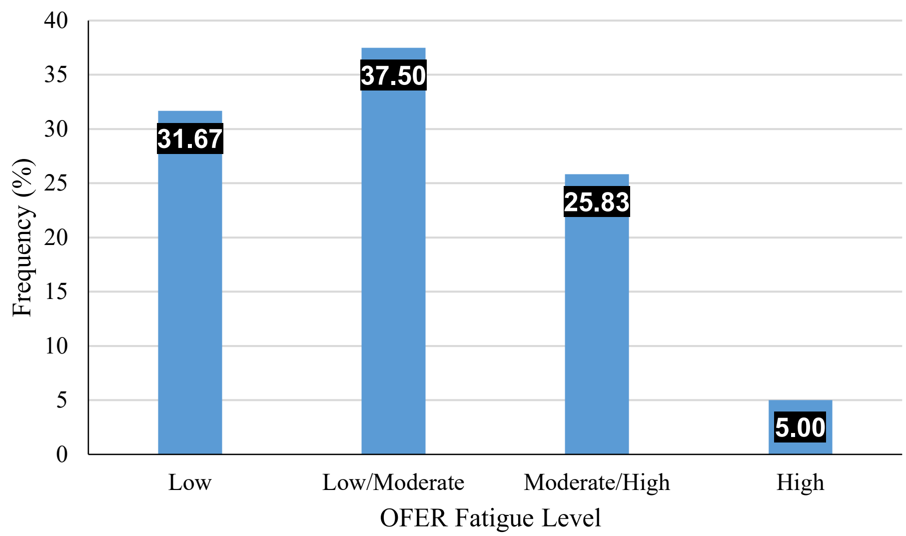

Figure.1. Measured fatigue level distribution (OFER Scale).

The second objective of the study was to evaluate the statistical correlation between demographic variables like age, construction experience, and fatigue level. The integrated data were statistically tested, and no statistical correlation (p-value=0.54) was supported by the data on age and fatigue level. Further, the data showed that there is no correlation between construction experience and fatigue level (p-value=0.20).

Research Implication

The current study attempt to investigate the prevalence of fatigue among construction workers in some active projects in the United States. The result reveals the prevalence of fatigue levels of moderate/high and high levels are above 30%, and most of the surveyed workers have reported that high and low/moderate intensity of acute and inter-shift recovery fatigue levels have experienced, respectively. This data's findings should serve as a warning to researchers and planners in the construction industry to put in place some interventions to lessen workers' acute exhaustion and speed up their recovery because chronic exhaustion can result from prolonged acute exhaustion and a rise in occupational accidents.

Conclusion

Perception of the prevalence of fatigue can improve the construction environment because workers are most prone to fatigue in construction projects due to doing physical and mental work every day. A large number of accidents are attributed to fatigue. However, the prevalence of it has not been studied as researchers have focused more on fatigue effect on other variables.

To address this knowledge gap, the current study explores the prevalence of fatigue among construction workers using a verified scale of fatigue measurement (OFER). The study data collection was conducted from 120 workers in various construction projects such as residential buildings and Institutional and Commercial buildings. The highest rates of the surveyed workers were on these types of projects.

A closer examination of the data revealed the prevalence of fatigue is approximately 34% and the fatigue level of most of the surveyed participants is low/moderate (37.50%). More specifically, workers have complained further from acute fatigue, among three dimensions of the OFER questionnaire, and a high level of acute fatigue was reported. In addition, the hypothesis that the mean age and construction experience of fatigued workers is statistically significantly higher than not-fatigued workers were tested. The survey found no correspondence among age, construction experience, and measured fatigue levels of workers.

This study provides an understanding of the prevalence of fatigue in construction as a contributing factor to accidents. The finding of this research is crucial for safety professionals to take effective mitigation strategies in order to implement better workplace practices the decrement the impact of fatigue. Perception of the causes, symptoms of fatigue, and ways to control fatigue in the workplace should be considered in future studies.

References

Abukhashabah, E., A. Summan, and M. Balkhyour. 2019. “Causes of occupational accidents and injuries in construction industry in Jeddah City.” *JKAU Met Env Arid Land Agric Sci*, 28 (1): 105–116.

Al-Bayati, A. 2022. “Construction Safety Culture & Climate: The Relative Importance of Contributing Factors.” *Prof. Saf.*, 67 (02): 24–28. OnePetro.

Aratake, Y., K. Tanaka, K. Wada, M. Watanabe, N. Katoh, Y. Sakata, and Y. Aizawa. 2007. “Development of Japanese version of the checklist individual strength questionnaire in a working population.” *J. Occup. Health*, 49 (6): 453–460. Japan Society for Occupational Health.

Bendak, S., and H. S. Rashid. 2020. “Fatigue in aviation: A systematic review of the literature.” *Int. J. Ind. Ergon.*, 76: 102928. Elsevier.

Bhuanantanondh, P., P. Bandidcharoenlert, W. Jalayondeja, C. Jalayondeja, and K. Mekhora. 2021. “Fatigue assessment among onshore oil rig shift workers in Thailand.” *Int. J. Ind. Ergon.*, 83: 103137. Elsevier.

Bussier, M. J. P., and H.-Y. Chong. 2022. “Relationship between safety measures and human error in the construction industry: working at heights.” *Int. J. Occup. Saf. Ergon.*, 28 (1): 162–173. Taylor & Francis.

Christian, M. S., J. C. Bradley, J. C. Wallace, and M. J. Burke. 2009. “Workplace safety: a meta-analysis of the roles of person and situation factors.” *J. Appl. Psychol.*, 94 (5): 1103. American Psychological Association.

Ibrahim, A., C. Nnaji, and M. Shakouri. 2022. “Influence of Sociodemographic Factors on Construction Fieldworkers’ Safety Risk Assessments.” *Sustainability*, 14 (1). https://doi.org/10.3390/su14010111.

Kashmiri, D., F. Taherpour, M. Namian, and E. Ghiasvand. 2020. “Role of safety attitude: Impact on hazard recognition and safety risk perception.” 583–590. American Society of Civil Engineers Reston, VA.

Li, H., D. Wang, J. Chen, X. Luo, J. Li, and X. Xing. 2019. “Pre-service fatigue screening for construction workers through wearable EEG-based signal spectral analysis.” *Autom. Constr.*, 106: 102851. Elsevier.

Lu, L., F. M. Megahed, R. F. Sesek, and L. A. Cavuoto. 2017. “A survey of the prevalence of fatigue, its precursors and individual coping mechanisms among U.S. manufacturing workers.” *Appl. Ergon.*, 65: 139–151. Elsevier.

Namian, M., A. Albert, and J. Feng. 2018. “Effect of Distraction on Hazard Recognition and Safety Risk Perception.” *J. Constr. Eng. Manag.*, 144 (4): 04018008. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001459.

Namian, M., A. Albert, C. M. Zuluaga, and M. Behm. 2016. “Role of Safety Training: Impact on Hazard Recognition and Safety Risk Perception.” *J. Constr. Eng. Manag.*, 142 (12): 04016073. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001198.

Namian, M., Z. Ghorbani, F. Taherpour, E. Ghiasvand, and A. Karji. 2022a. “Demystifying the Impact of Age on Safety Performance of Construction Workers: Examining the Mediating Roles of Experience and Fatigue.” *Pract. Period. Struct. Des. Constr.*, 27 (4): 04022038. https://doi.org/10.1061/(ASCE)SC.1943-5576.0000718.

Namian, M., D. Hollar, F. Taherpour, and E. Ghiasvand. 2020. “Deciphering Why ‘Cursed Construction Workers’ are More Vulnerable to Occupational Accidents.” *EPiC Ser. Built Environ.*, 1: 491–498. EasyChair.

Namian, M., M. Tafazzoli, A. J. Al-Bayati, and S. Kermanshachi. 2022b. “Are Construction Managers from Mars and Workers from Venus? Exploring Differences in Construction Safety Perception of Two Key Field Stakeholders.” *Int. J. Environ. Res. Public. Health*, 19 (10): 6172. Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/ijerph19106172.

Namian, M., F. Taherpour, E. Ghiasvand, and Y. Turkan. 2021. “Insidious Safety Threat of Fatigue: Investigating Construction Workers’ Risk of Accident Due to Fatigue.” *J. Constr. Eng. Manag.*, 147 (12): 04021162. https://doi.org/10.1061/(ASCE)CO.1943-7862.0002180.

Pandit, B., A. Albert, Y. Patil, and A. J. Al-Bayati. 2019. “Impact of safety climate on hazard recognition and safety risk perception.” *Saf. Sci.*, 113: 44–53. https://doi.org/10.1016/j.ssci.2018.11.020.

Parijat, P., and T. E. Lockhart. 2008. “Effects of lower extremity muscle fatigue on the outcomes of slip-induced falls.” *Ergonomics*, 51 (12): 1873–1884. Taylor & Francis.

Rajaratnam, S. M., and J. Arendt. 2001. “Health in a 24-h society.” *The Lancet*, 358 (9286): 999–1005. Elsevier.

Sari, R. P., B. N. A. Susanto, and E. Komalasari. 2021. “The correlation between work shift and level of fatigue among workers.” *Enferm. Clínica*, 31: S450–S453. Elsevier.

Winwood, P., A. Winefield, D. Dawson, and K. Lushington. 2005. “Development and validation of a scale to measure work-related fatigue and recovery: the Occupational Fatigue Exhaustion/Recovery Scale (OFER).” *J. Occup. Environ. Med.*, 594–606. JSTOR.

Xing, X., B. Zhong, H. Luo, T. Rose, J. Li, and M. F. Antwi-Afari. 2020. “Effects of physical fatigue on the induction of mental fatigue of construction workers: A pilot study based on a neurophysiological approach.” *Autom. Constr.*, 120: 103381. Elsevier.

Xu, S., and N. G. Hall. 2021. “Fatigue, personnel scheduling and operations: Review and research opportunities.” *Eur. J. Oper. Res.*, 295 (3): 807–822. Elsevier.

Yu, Y., H. Li, X. Yang, L. Kong, X. Luo, and A. Y. Wong. 2019. “An automatic and non-invasive physical fatigue assessment method for construction workers.” *Autom. Constr.*, 103: 1–12. Elsevier.

Zhang, M., L. Murphy, D. Fang, and A. Caban-Martinez. 2015. “Influence of fatigue on construction workers’ physical and cognitive function.” *Occup. Med.*, 65 (3): 245–250. Oxford University Press U.K.