Lecture Notes in Civil Engineering

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M. Shahria Alam · Ashraf el Damatty ·
Gordon Lovegrove *Editors*

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CSCE21 Construction Track Volume 1

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Dr. Gordon Lovegrove is MBA/Civil Engineer with over 30 years of experience in smarter growth, housing, sustainable transportation, safety, economics, and project management. He was the point man that got the award-winning Universal Transportation Pass (U-Pass) for UBC that tripled transit use at both campuses. His current research focus is on zero-emission, hydrogen-powered rail (hydrail), including several industry partnerships to develop Canada's first hydrail switcher locomotive. He is founding partner of the SMARTer Growth Partnership (smartergrowthpartnership.ca), Associate Professor/Founding Member of UBCO's School of Engineering (ok.ubc.ca), VP Technical Programs for the Canadian Society of Civil Engineering (csce.ca), and Co-author of several best practice guides on sustainable development, health, and safety. He brings 20 years of practical industry development experience plus 14 years of engineering research and design expertise. His research team includes electrical, mechanical, and civil engineering graduate students, plus computer science coders and research assistants.

Interdependencies of Lifelines: A Case Study of Transportation Infrastructure Under Hurricane Impacts

Long D. Nguyen, Alexis Slobodzian, Claude Villiers, and Seneshaw Tsegaye

1 Introduction

The infrastructure lifelines are critical systems for counties, states and/or nations to function and provide essential services to the public. Natural disasters negatively affect communities and civil infrastructure [8]. According to the National Association of Counties [13], four main infrastructure lifelines that apply to every county across the United States are energy, water, transportation, and communications. These lifelines are more exposed to natural hazards like hurricanes, which bring strong winds, storm surges and floods, which in turn cause outages of these lifelines. The interdependency between the lifelines can further amplify the outages. For example, a hurricane knocks down power lines (energy) which in turn can interrupt water and wastewater treatments (water), traffic signals (transportation) and telephone and Internet (communications).

Southwest Florida experienced the damage of these lifelines caused by Hurricane Irma and its aftermath in 2017—the top five most destructive and costliest hurricane since 1980 according to the Federal Emergency Management Agency [5]. The outages of the lifelines collectively increase the vulnerability of vital services such as hospitals, schools, and shelters/housing and prolong the recovery times of these services. For example, in the month of Hurricane Irma, 16 schooldays were lost in Lee and Collier County School Districts. This study aimed to assess (i) the direct impacts of Hurricane Irma on county transportation infrastructure—one of the four primary infrastructure lifelines and (ii) the dependencies of this infrastructure on the other

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lifelines during the course of recovery after the hurricane impacts. While extant research on infrastructure resilience has contributed greatly to understandings of transportation performance under the disturbances of extreme events, this study fills a gap in our understanding the dependencies of transportation infrastructure during recovery. The subject of this study was the transportation infrastructure owned and maintained by Collier and Lee counties in Southwest Florida, USA. Specifically, Collier County Transportation Engineering Division (Collier DOT) and Lee County Department of Transportation (Lee DOT) were participated in this study.

2 Context

This section presents the theoretical background and the study area and methodology. The theory background briefly highlights recent related studies and the concepts of infrastructure dependencies that were used in this study. The study area and methodology describe the subject and research methods employed.

2.1 Theoretical Background

Extreme events can hinder transportation infrastructure performance which in turn impacts on interdependent systems and affects a community through disruptions in service [15]. Roads, rails, and ports are among the first critical infrastructure that requires attention to enable transport of relief supplies and responders after severe natural disasters [18]. As one of the most massive storms on record, Hurricane Irma caused state and local governments in Florida issued evacuation orders that affected over six million people and sheltered more than 77,000 residents [7]. A study on the impact of Hurricane Hermine in the City of Tallahassee, Florida demonstrated that the biggest hospital in the city could hamper emergency response during hurricanes when it experienced substantial roadway closures in the vicinity [9]. Previous empirical studies on vulnerability of transportation networks tended to focus on high population density areas such as big cities, for example, the City of Orlando, Florida under the 2004 hurricane season [2] or New York subway system under Hurricane Sandy [3]. However, using Hurricane Irma's impact on Florida as a case study, Mitsova et al. [12] showed that the rural counties "*experienced longer power outages and much slower and uneven restoration times*." The current study therefore targeted on moderately populous areas, i.e., Lee and Collier counties.

Dependency and interdependency are two related concepts in critical infrastructure studies. Rinaldi et al. [16] defined: (i) dependency as a "*linkage or connection between two infrastructures, by which the state of one infrastructure influences or is reliant upon the state of the other*;" and (ii) interdependency as a "*bidirectional relationship between two infrastructures in which the state of each infrastructure influences or is reliant upon the state of the other*." Since only focusing on one

Table 1 Types of dependencies

Dependency type	Definition*
Physical	An infrastructure is physically dependent if the state of its operations is dependent on the material output(s) of another infrastructure through a functional and structural linkage between the inputs and outputs of two assets
Cyber	An infrastructure has a cyber dependency if its state of operation depends on information and data transmitted through the information infrastructure via electronic or informational links
Geographic	Infrastructure assets are geographically dependent if a local environmental event can create changes in the state of operations in all of them
Logical	An infrastructure is logically dependent if its state of operations depends on the state of another infrastructure via a mechanism that is not a physical, cyber, or geographic connection. Logical dependency is attributable to human decisions and actions and is not the result of physical or cyber processes

*Based on Rinaldi et al. [16] and Petit et al. [14]

infrastructure lifeline (i.e., transportation), this paper presents only the assessment of the dependencies of transportation infrastructure on other critical infrastructures during its recovery process after Irma. Interdependencies among these infrastructure lifelines were not within the scope of this paper. Dependencies are further classified as physical, cyber, geographic and logical (Table 1).

2.2 *The Study Area and Methodology*

The study area is Lee and Collier counties in Southwest Florida. The area was directly hit by Hurricane Irma at category 3 and then transitioning to category 2 on September 10, 2017 (Fig. 1). For transportation infrastructure, Collier DOT and Lee DOT participated in this study. Collier DOT has owned and managed transportation infrastructure throughout Collier County, except the cities of Naples and Macro Island. The Lee DOT has owned and managed most of transportation infrastructure in Lee County, including the cities of Fort Myers and Fort Myers Beach. Transportation infrastructure within these two counties that was owned and managed by other entities (e.g., Florida DOT, the City of Naples) was not in the scope of the current study.

Both secondary and primary data were collected from the bi-county DOTs in 2019. The DOTs were first asked to provide Hurricane Irma related data. These secondary data were to provide the direct impact of Hurricane Irma on the transportation systems. Group interviews were then scheduled with these DOTs. The group interview setting was selected as the interview questions covered many aspects that require expertise from various individuals with different roles. The chief traffic operation engineer and the financial and operations support manager of Collier DOT participated in the group interview. With Lee DOT, four individuals consisting of the senior engineer, traffic operation senior manager, public works project manager

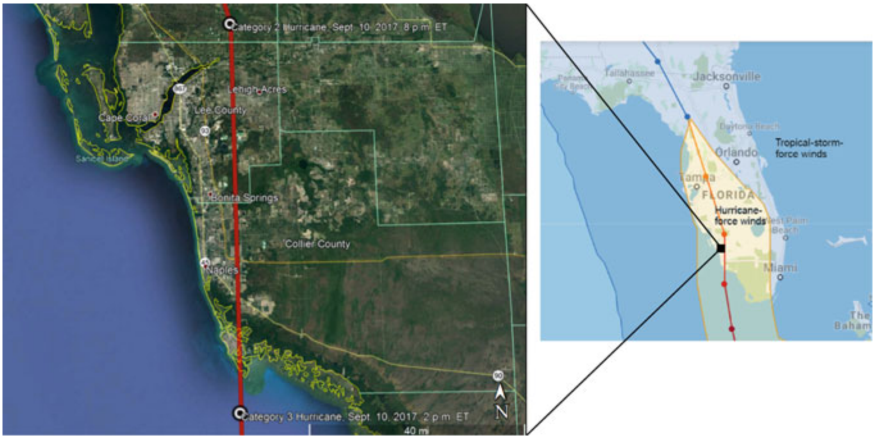

Fig. 1 Study area map with approximate Hurricane Irma path. *Source* Left map from Google Earth; right map from Almukhtar et al. [1]

and senior database analyst participated in the group interview. A set of 26 open-ended questions were prepared and sent to these participants prior to the meetings. The interview questions were mainly to assess the extent that transportation infrastructure depended on three other infrastructure lifelines, namely energy, water and communications during its recovery.

3 Results and Discussion

This section discusses the major findings of the current study. The section starts with the direct impacts of Hurricane Irma on the transportation infrastructure and then presents the dependencies of the transportation infrastructure during the recovery.

3.1 Direct Hurricane Impacts on Transportation Infrastructure

The direct impacts of Hurricane Irma were extensive in the two counties. Lee County [10] estimated its county-wide damage of $833 million, including the residential loss (87.2%), commercial loss (12.3%) and other loss (0.5%). Property damage in unincorporated areas in Collier County alone was estimated about $320 million [17]. The overall damage of Hurricane Irma has been documented and published by various agencies.

The damage of transportation infrastructure was also considerable. After the hurricane, DOT employees were deployed to assess the damage of their infrastructures.

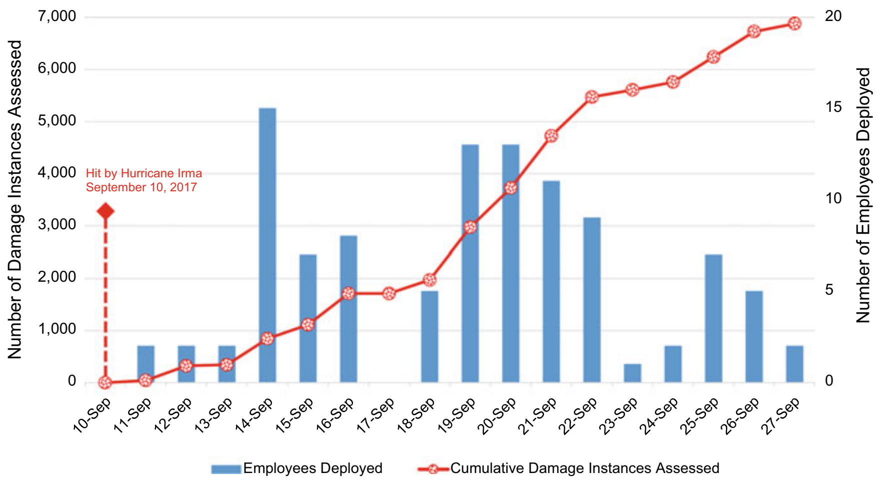

Fig. 2 Collier DOT roadway signs damage with employees deployed after Hurricane Irma

Figure 2 displays the cumulative damage instances assessed as well as the number of field employees deployed by Collier DOT in the first three weeks after Irma. A total of 7000 roadway sign damage instances out of 30,000 signs in service were identified and assessed by the employees. On a peak day of September 14, 2017, 15 employees were on the county's roadways to assess the damage.

The damage of the Lee County's transportation infrastructure was similar. For example, approximately 10,000 roadway signs were damaged throughout Lee County (Fig. 3). The cost of repair for the damage was almost $200,000. As shown in Fig. 3, two-thirds of the sign damage were identified in Lehigh Acres in the eastern Lee County. This indicates the vulnerability of the transportation infrastructure in that specific area of the county.

The damage caused by Irma to transportation infrastructure managed by each of the two county DOTs was well above a million dollars. Table 2 summarizes the repair costs of Collier DOT. Major repair costs are for street name signs, street lights and traffic signals. The pre- and post-Irma non-asset tasks such as shelter signs, road under water signs, temporary traffic control, recovery center traffic control, etc. incurred additional costs to the DOTs, for example more than $35,000 to Lee DOT [11].

3.2 Dependencies of Transportation Infrastructure in Recovery After Hurricane Irma

While the damage caused by the hurricane on transportation infrastructure could be independently identified and assessed by these DOTs, the course of recovery relied

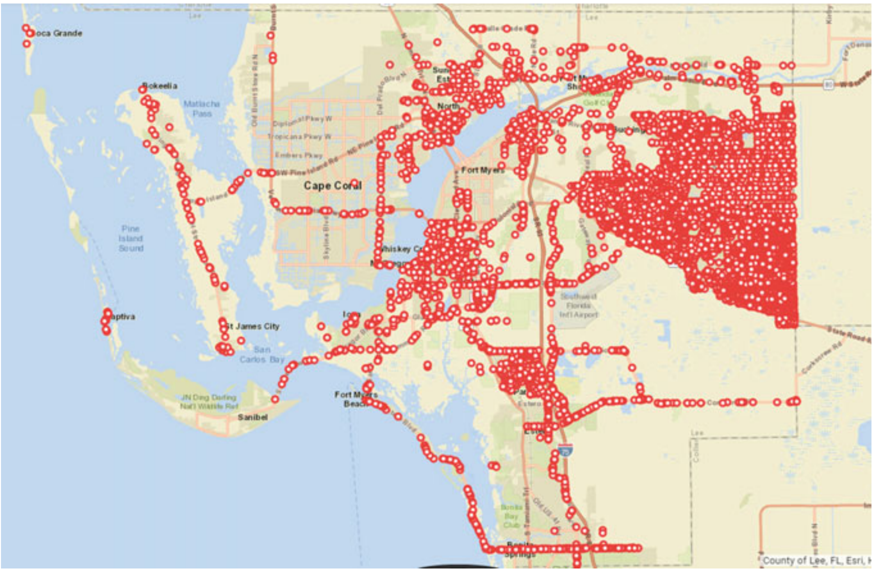

Fig. 3 Lee DOT post Hurricane Irma sign repair tasks. *Source* Lee DOT [11]

Table 2 Collier DOT repair costs caused by Irma

Damage type	Repair costs* (US Dollars)
Street name signs	$460,000
Street lights	$430,000
Traffic signals	$390,000
Total	$1,280,000

*Amounts not including the department's labor costs

on many other agencies, institutions and infrastructure lifelines. From the group interviews with the two DOTs, Fig. 4 demonstrates the major dependencies of the transportation infrastructure during its recovery. The transportation infrastructure in this study includes bridges/roadways, traffic operations, traffic signals, closed circuit TV (CCTV), traffic signs and street lights.

Based on the classification of dependencies from literature (Table 1), the dependencies of transportation infrastructure on other lifelines can be physical, cyber, geographic and logical (Fig. 4). The line thickness conceptually indicates the level of improvement needed on the associated dependency to improve resilience and recovery of transportation infrastructure in response to future hurricanes. The line thickness was determined by the authors based on the responses of the participants in the group interviews of the two DOTs.

Energy was considered the most important infrastructure lifeline affecting the transportation systems. In fact, all signalized intersections, including more than 200

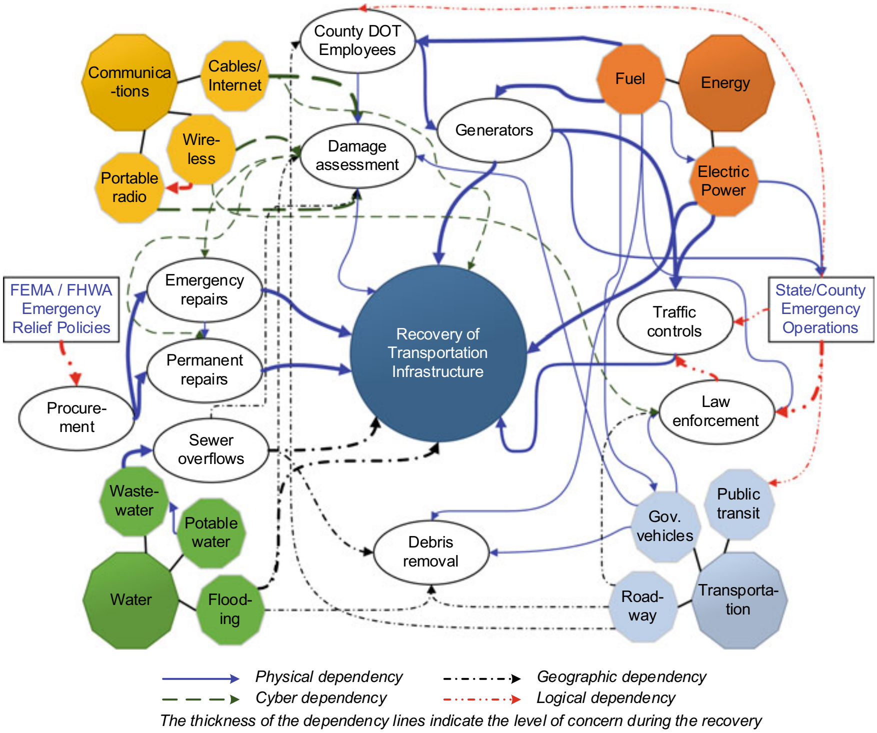

Fig. 4 Dependencies of county transportation infrastructure in recovery from hurricanes

and 400 owned and managed by Collier DOT and Lee DOT, respectively, were without electric power at least at one point in time after Hurricane Irma passed. The power outage affected not only traffic signals at the intersections but also traffic lights and traffic operations and controls (Fig. 4). Four days after Irma, only 3 out of 16 signals that were checked by Lee DOT employees were back on line [11]. As another source of energy, fuel plays a critical role during power outage. Both counties had their own gas stations to meet their needs (e.g., generators). However, due to the shortage of fuel supply in the area after the hurricane, employees and contractors did not have gas to fuel their own vehicles to work. The lack of this fuel access negatively affected initial recovery tasks such as damage assessment, refilling fuel to generators throughout the transportation systems and emergency repairs (Fig. 4). According to Lee DOT, running generators was the biggest nuisance as they ran out of fuel easily. The last generator was still deployed by Lee DOT two months after the storm event. In addition, the fact that Collier DOT building had no power for one week due to no back-up power affected traffic operations, brought its server down, and limited work space to its employees.

Transportation recovery had dependencies on the recovery of water infrastructure due to wastewater overflows and flooding. Due to no power for lift stations, sanitary sewer overflows (SSO) occurred on roadways in some areas of both counties. Street flooding also occurred in some areas. Roadway accessibility, damage assessment and debris removal geographically depended on the SSO cleanups and flooding (Fig. 4). Nevertheless, both DOTs considered that the dependencies of transportation infrastructure recovery on water infrastructure were minimal for most parts of their transportation networks.

Communications systems including cables, wireline, wireless services and Internet played a critical role in transportation recovery. While the hurricane caused minimal damage to fiber optic cables owned by the two DOTs, wireless services and Internet in the study area were significantly impacted. According to the Federal Communications Commission [4], 160 out of 212 cell sites (75.5%) in Collier County and 186 out of 343 cell sites (54.2%) in Lee County were out of service one day after Irma. Without cell services and Internet, DOT staff had to bring papers to do field work and had to have data entry thereafter as cyber dependencies shown in Fig. 4. The outage also caused difficulty in getting people back to work. In areas that the DOTs did not have their own fiber optic cables, they relied on the cables of other service providers such as in Fort Myers Beach, Lee County. The county had to provide fuel to these providers to bring their service back. Due to the importance of communications during storms and the unpleasant experience during Irma, Collier DOT recently purchased hand-held radios for a total of $50,000 for future hazards.

The county DOTs also physically depended on their own infrastructures such as roadways, public transit and vehicles during the recovery process. The DOTs had to do some clearance with limbs and falling trees on their roadways. These were the first tasks to perform after the hurricane passed. The limbs and debris were put aside and piled up for county solid waste management to collect later, which could take months. Lee DOT for example had more than 1200 tasks for two different work orders, 605 tasks of category A tree removals and 638 tasks of category B emergency measures.

The logical dependencies on local, state and federal agencies were also highlighted in the interviews with the two DOTs. The emergency relief policies of FEMA and Federal Highway Administration (FHWA) affected the recovery of local transportation infrastructure. Under the policies of FHWA [6], emergency repairs and permanent repairs are the two categories of emergency relief. Emergency repairs are "*undertaken during or immediately after a disaster to restore essential traffic, to minimize the extent of damage, or to protect the remaining facilities*" while permanent repairs are "*undertaken after the occurrence of a disaster to restore the highway to its pre-disaster condition*" [6]. The policy could negatively affect the recovery time and efficiency. For example, with the intersections having multiple traffic signal heads, only one head was repaired in one traffic direction as an emergency repair. FHWA policies required competitive bids before contractors came back to conduct permanent repairs and fix other heads. The permanent repairs therefore could take months or years after the disaster as experienced by Collier DOT. Unless the emergency relief policies are changed, county DOTs may solicit competitive bids to select "recovery" contractors to save procurement lead time and quickly respond to future storm events as Collier DOT recently did after they experienced unnecessarily lengthy repairs after Hurricane Irma hit. The coordination with the local law enforcement was experienced differently by the two DOTs. Collier DOT had no issue in coordinating with law enforcement which took place in the county emergency operations center (EOC). The coordination with local law enforcement to direct traffics when power outage occurred at intersections seemed to concern Lee DOT in overall. Nevertheless, the law enforcements in the cities of Cape Coral and Fort Myers directed the traffics in their jurisdictions in Lee County. Effective coordination with local law enforcement definitely strengthens the resilience of the transportation infrastructure.

4 Conclusions

This study assessed the direct impacts of Hurricane Irma on transportation infrastructure and especially the dependencies of this infrastructure during the course of its recovery in two counties in Southwest Florida. The damage caused by Irma on street signs, street lights and traffic signals owned and managed by each county DOT was well above $1 million. Other infrastructure lifelines included in the assessment of the physical, cyber, geographic and logical dependencies of transportation infrastructure were energy, water and communications. The restoration of electric power and wireless services was found to be crucial to initial recovery efforts. Proactively soliciting competitive bids to select “recovery” contractors in advance can improve efficiency and restoration process to bring the infrastructure to its pre-disaster condition without compromising the federal emergency relief policies.

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Constructability in the Design Process: A Review of Current Practice Within the UK Construction Industry

P. Nolan and G. Gibson Jr.

1 Introduction

The UK has a long-term productivity problem, underperforming when compared to other developed nations, which has been recognised by the UK Government [15]. The manufacturing industry has nearly doubled productivity in the last two decades, whereas the construction industry has remained stagnant [14]. While there is possibly positive productivity growth in the North American construction industry [26], the construction industry globally has significantly underperformed when compared to other industries. The UK construction industry's productivity challenge is common knowledge within the industry and discussed widely outside of the industry [23]. The construction industry differs from many other industries in that its largely separate operations are carried out by individual designers and constructors, changing this culture is key to increasing efficiency and quality in construction [10]. Rethinking the design process with a greater focus on constructability has been reported to have significant potential benefits, contributing to an 8–10% growth in productivity [2].

Constructability, as defined by the Construction Industry Institute (CII), is "the optimum use of construction knowledge and experience in planning, design, procurement, and field operations to achieve overall project objectives" [4]. Constructability is a specific term used to describe how efficiently a construction project can be realised on site. While the term has been used for many years, there is a lack of quantitative

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data on the implications of a design decision on construction outcomes, leading to constructability being associated with "best-practice" and "common-sense".

While there is a significant amount of literature on the topic of constructability, there is limited information for the current practice within the UK construction industry design sector. Due to the lack of existing information, this research investigation took an exploratory approach to clearly define the subject, with the following research foci framing the investigation: (1) current practice for the incorporation of constructability in the design process, within UK construction industry design firms; (2) current awareness and knowledge of constructability within UK construction industry design firms; and (3) identification of opportunities and barriers for increasing consideration of constructability in the design process, within UK construction industry design firms [22].

2 Literature Review

Research in the area of constructability and buildability has historically been focused in the UK, USA and Australia, spanning over the last 50 years [4, 5, 7]. Most recently, developments have been in South East Asia, such as Singapore and Hong Kong [6, 9].

The terms buildability and constructability have been used widely and have several definitions, but the ones seen as the benchmark within the existing body of research are as follows. Buildability, as defined by the Construction Industry Research and Information Association (CIRIA), is "the extent to which the design of a building facilitates ease of construction, subject to overall requirements for the completed building" [7]. The CII definition was provided earlier in the paper. While this paper has adopted the CIRIA and CII definitions for buildability and constructability, there are numerous variations to these definitions within the body of existing research. There are similarities between the concepts of buildability and constructability, and there are some differences. Buildability is predominantly focused on how the design stage of a project influences the ease of construction on-site, while constructability is a broader concept which takes a more holistic view of the project. The term constructability will be used to cover both buildability and constructability, for ease of reading for the rest of the document.

Several research studies have looked into how constructability can be evaluated in the design phase of projects through the use of constructability reviews and quantitative assessments [18]. While these have shown how improvement can be achieved, there is still work to be done to achieve the theorised potential improvements to the construction industry's productivity [2]. In addition to the research into the collection of quantitative data, there has been work towards developing a framework for which constructability can be assessed within the design phase [13]. This area is key to developing approaches for integrating constructability successfully into the design phase of projects.

There are many different tools for design constructability, which have been reviewed in several studies. These can be grouped into three approaches for incorporation within the design process:

1. Quantitative assessment is a process to generate a quantum to enable an objective evaluation. There have been several studies of various quantitative approaches [20, 27, 30, 31].
2. Constructability reviews, like the name suggests, are a systematic review of a design using a formal process. The review would be completed during the design process, either at a single stage or multiple stages during the design development, to evaluate a design, and through construction knowledge and experience, identify where improvements can be achieved [25]. The construction review is ultimately owned by the client, but there are numerous stakeholders from the different stages of the project.
3. Constructability Programmes involve incorporating formal construction input with all stages of the design process, from conceptual design through to detailed design delivery. This input would typically be from the contractor who will be responsible for the construction. An example of a constructability programme would be Early Contractor Involvement (ECI). Two significant studies on implementing constructability programmes at various project stages are Kog et al. [19] and Jergeas et al. [17].

The area of technology-based tools to help with quantitative assessments has recently been an area of great interest. A recent paper collected quantitative data to support this work, looking into the implications of beamless or beam-supported reinforced concrete slabs on construction productivity [16]. Objective data from these types of studies can be used to assess and support design decisions, enabling perhaps better design decisions. But to date, there are a limited number of studies in this area.

Previous studies in North America have shown that constructability has gained acceptance throughout the construction industry there, and is increasingly being applied to projects [1, 24]. In addition to this, there have been several developments in Hong Kong and Singapore for constructability design standards and legislation [29]. These studies have identified the following barriers:

- Lack of clear clients' briefing, identifying essential project requirements and restrictions.
- Designers' insufficient knowledge and experience of practical construction methods.
- Lack of contractor involvement at the early stages of projects.
- Insufficient time or fee allocated for design work.
- Construction details defined not by the designer, but by tradespeople later in the project.

The literature, though not focused on the UK, does provide an easily translatable comparison for this study to identify similarities and differences. There seems to be a 'gap' in the knowledge of how to incorporate constructability into the design phase that does not solely rely on the experience and judgements of individuals. This is particularly evident for the UK construction industry, where the authors were unable to find existing data on the current practices for incorporating constructability within the design process. Therefore, the research took an exploratory approach due to the lack of existing information on the subject.

3 Research Methodology

A qualitative, semi-structured interview research method was selected to collect primary data to answer the research questions. By using a systematic approach to data collection and analysis, an understanding of the problem from the data was generated, through the discovery of emerging patterns [8]. The conceptualised patterns and structure were developed using an inductive approach to define general principles from specific observations [3, 8]. This enabled the authors to make conclusions on the current practice within the UK construction industry design firms, through the views, experiences, and opinions of current industry professionals.

Twenty semi-structured interviews were completed, with participants representing ten UK construction organisations. The interviews were carried out either in-person or via video conference calls between the authors and the individual participant. Interviews were digitally recorded, anonymized, and subsequently transcribed for text data analysis. These text data were checked before being analysed in an inductive thematic process using the interview transcripts, interview recordings and author notes [8].

As the authors have used purposeful sample selection, there is the opportunity for bias in participant selection to affect the findings. Furthermore, there is also the potential for the researcher to influence participants responses during interviews inadvertently. All findings presented are valid for the sample as presented, but caution should be taken in generalizing to the broader population. Future work could look to establish a more conclusive finding using alternative methods, such as a survey with a large sample size enabling a statistical significance to be established.

A breakdown of the interview participants is shown in Table 1, using anonymized participant and organisation identification. It gives a breakdown of the participant's role, title, and years of experience, as well as the method used to complete the interview. In total, the sample participants had 337 years of professional experience, with a mean of 17 years per participant, with a range from three to 44 years.

Eight of the participants were from a single organisation, representing 40% of the sample, as shown in Table 2. This was used to look at an organisation in greater depth, helping to understand the potential for variation within organisations. However, it is acknowledged this potentially introduced bias into the sample through the over-representation of one organisation. To mitigate this, the participants' organisation affiliation was considered during the analysis of the data.

As shown in Table 2, organisations represented by the participants ranged in scale from large global consultancies to smaller UK-only based design firms. Five of the

Table 1 Interview participant information

Participant ID	Organization ID	Role	Years of experience	Interview method
I-01	O-01	Principal engineer	10	Phone
I-02	O-02	Senior engineer	11	Phone
I-03	O-02	Engineer	6	Phone
I-04	O-02	Senior engineer	7	Phone
I-05	O-03	Principal engineer	9	In-person
I-06	O-03	Associate engineer	13	In-person
I-07	O-03	Director	20	In-person
I-08	O-03	Associate director	32	Phone
I-09	O-03	Associate director	20	In-person
I-10	O-03	Principal engineer	9	In-person
I-11	O-03	Principal engineer	9	Phone
I-12	O-03	Director	26	Phone
I-13	O-04	Managing director	44	In-person
I-14	O-05	Senior engineer	8	Phone
I-15	O-05	Associate	10	Phone
I-16	O-06	Director	19	Phone
I-17	O-07	Engineer	3	Phone
I-18	O-08	Associated director	15	Phone
I-19	O-09	Managing director	30	Phone
I-20	O-10	Managing director	36	In-person

Notes
Participant ID—anonymized identification number of interviewees
Organisation ID—anonymized identification number of interviewees employing organisation
Role—rationalised job title of the interviewee to enable comparison of role during analysis
Years of experience—the number of years the interviewee has worked as a professional within the construction industry as a designer
Interview method—the method used to complete the interview

ten organisations were in the top 40 global design firms [12] and were therefore considered to provide data on what would be considered good current practice.

4 Results and Discussion

The findings of the research have been broken down into three sections, which respond to the research questions; and several themes identified within each of them as outlined below.

Table 2 Organization size and region of operations for the interview participants

Organization ID	Approximate organization size, based on the number of employees	Regions of operation*	Number of participants in sample (% of sample)
O-01	10,001 plus	Global	1 (5%)
O-02	10,001 plus	Global	3 (15%)
O-03	10,001 plus	Global	8 (40%)
O-04	10,001 plus	Global	1 (5%)
O-05	501–1000	UK based	2 (10%)
O-06	501–1000	Multinational	1 (5%)
O-07	51–200	UK based	1 (5%)
O-08	51–200	Multinational	1 (5%)
O-09	11–50	UK based	1 (5%)
O-10	11–50	Multinational	1 (5%)

*Regions of operation describe the scope of the organisation's activities and active markets. Global refers to organisations with construction projects and presence in all geographic locations, Multinational refers to organisations with a presence in several countries but not globally. UK based refers to organisations that operate solely on UK construction projects

4.1 Practice

4.1.1 Process

The majority of survey participants, 16 out of 20, did not follow an explicitly formal constructability process. When asked, for example, Participant I-15 stated, "not a formal construction review, but that is not to say that we have not been considering construction as an element of the works". While they were not following formal processes, there was a consideration of constructability through a technical review, carried out as part of the quality assurance process by a peer-review of senior technical specialists. Constructability was just one design aspect that was reviewed, "we do not have explicit constructability reviews, but it has certainly been one of the things that we have touched on when we have done design reviews" (Participant I-10). The processes being used were very reliant on subjective decisions, with no examples of objective decisions being made based on quantitative assessments. While this is not inherently flawed, it does make the process limited to the person involved in the design project.

Four participants provided descriptions of formal approaches for considering constructability. These formal approaches could be categorised into three groups: firstly, projects within regulated industries such as rail, secondly major projects of massive scale, and thirdly unique individual team processes. For rail projects, consideration of constructability is to ensure minimal disruption to the existing assets, which is a primary decision factor in awarding work, and subsequent design decisions. For major projects of significant scale and scope, such as new nuclear power stations, contractors are included within the early procurement activities to ensure constructable delivery. Constructability programmes are adopted through early contractor engagement, embedding contractor employees within the design office. An example of a unique individual team process, that was not knowingly used by the broader organisation, was from a participant associated with Design & Build procurement within the water sector where the team had developed a series of ‘proforma’ lists, that could be described as constructability reviews.

The four survey participants providing examples of formal constructability reviews and programmes were from organisations O-02 and O-03, both of which are large global organisations and had multiple participants interviewed within the study. This also illustrates that there was a lack of consistency with approaches even within organisations. The areas where formal constructability reviews and constructability programmes were used, in either regulated industries or major projects, showed similarities in that there are “intelligent” clients involved. While there were similarities with the studies in the USA and Hong Kong [29], it was evident during the interview that there appears to be a different formal constructability environment within the UK design firms at least for the firms studied.

4.1.2 Design Criteria

From the informal constructability process, which was the majority of examples interview respondents provided, the use of design criteria to perform constructability was a theme identified in the analysis with all 16 participants. While they did not have a formal process for constructability, it was still considered during the design process and design reviews, as one of the criteria against which a design could be evaluated. Other design criteria mentioned include technical accuracy, sustainability, and perceived cost. Several participants acknowledged challenges with weighting the importance of these design criteria, and that there were potential conflicts between criteria. For instance, participant I-03 stated, “there can be conflict I guess, between what is perhaps the optimum design in terms of say, the use of materials, compared to just making it easy for the contractor”.

As previously discussed, these design decisions were made without quantitative assessment and therefore could lead to flawed decision making. This is because decisions were made on perceived outcomes and subject to bias and other factors; this conflict of design criteria was identified in [29] study of Hong Kong construction industry practitioners, with the dilemma of balancing the reduction of material usage and increasing the complexity of design being specifically mentioned as a conflict. Participants struggled to describe the actual design processes where these decisions were made, generally responding vaguely to questions. This is likely due to the informal processes that they were using.

4.1.3 Design Decisions

Building on the design criteria theme, it was clear that design decisions were being made, not based on quantitative assessments, but through subjective decisions. Nineteen of the 20 participants stated that they make design decisions within their work to improve constructability, "based on their knowledge and experience and how they would want to approach a problem" (Participant I-04). This means they are using tacit knowledge to inform their decisions with is difficult to access because it is often not codified and may not necessarily be easily expressed.

This means that a qualitative and not quantitative process is being used. Participant I-18's statement typified this, "We do not get into the numbers in any detail really unless we have a specific temporary works design capacity". When probed further about potential tools that could be used, such a 3D modelling, generally participants responded that they were not used, for example, Participant I-10's response to how decisions are made, "not driven via digital tools in a quantitative way". Participant I-09 stated, "The difficulty we always had, was that that constructability advice was simply how somebody could build it rather than how somebody should or would build it".

The decision process revealed by the interviewees generally differed from the literature, which discussed the use of construction experts within design organisations), to provide construction advice on designs [24], there was no example of this within the interviews. The only construction experts identified were where formal constructability programmes were used, and contractor staff were embedded within the design team.

4.1.4 Procurement

Examples of active formal constructability processes, such as constructability reviews and construction programmes, were used when progressive procurement methods were present. While all participants interviewed were keen to incorporate constructability practices, they acknowledge that "it is very much been driven by the clients" (Participant I-08). One interviewee identified a particular project that was very progressive in incorporating formal constructability reviews during design with a robust constructability programme, stating the client has "the construction team already working with us" (Participant I-04). This was a project where the client had adopted a strong alliance procurement strategy and therefore enabled the constructability processes to be successfully implemented.

Respondents provided examples where designers have been prevented by the client, due to the procurement method, from bringing contractors in during the design phase. Participant I-15 stated, "we quite often ask the client to bring the contractor along to a design team meeting to specifically get their input", and explained this was met with mixed success. This was similar to previous studies [24, 29], where procurement and contract types were a significant barrier to good constructability practices. Progressive procurement strategies represent a small proportion of the construction industry in the UK. Therefore, if constructability is to be improved in the broader industry, consideration of how to overcome procurement barriers is essential.

4.2 Awareness and Knowledge

4.2.1 Awareness of Constructability Definition

All participants recognised the terms constructability and buildability and saw these as an essential consideration for designers. Participant I-18 commented, "Yes definitely it is the most important because if you cannot build it there is no point in designing it". However, while the terms were recognised and seen as necessary, there was limited specific knowledge. When the participant was presented with the CII and CIRIA definitions for constructability and buildability, participants were not aware of the specific definitions.

When the participants were asked about the performance of the construction industry with regards to constructability, there was general agreement, that while the industry performance was reasonable, there was significant room for improvement. Participant I-13 commented "…there is a lot of things we could improve" and "it is not necessarily as well thought through as it should be".

4.2.2 Safety Focus and Constructability

During the interviews, it became apparent that the participants had a strong association between constructability and the UK's Construction, Design and Management Regulations (CDM), 17 out of 20 commenting on this. CDM is a British specific regulation for managing the health, safety, and welfare of construction projects throughout the project lifecycle. It outlines specific responsibilities for designers, such that they eliminate, reduce, or control any foreseeable health and safety risks [28]. When asking about constructability on their project, participants regularly commented they did it as part of CDM, such as Participant I-08 stating "a lot of overlap there with CDM and health and safety". Similarly, Participant I-15 responded, when asked if they carry out any formal constructability assessments or reviews, "we certainly have a health and safety review on every project".

If designers are associating constructability to CDM regulations, this means they are making design decisions that focus on the health and safety aspects of the design, while not necessarily considering other project performance aspects, such as cost and productivity, with the same weight. It should be noted that this sample had a predominant focus on the infrastructure sector of the UK construction industry, which is known to have robust health, safety, and welfare culture. Further work to quantify the influence of CDM on design decisions, in comparison to other design criteria, could reveal the significance of this finding.

4.2.3 Education

A key theme within awareness and knowledge was the lack of formal education with regards to constructability. All participants within this study had received formal education at university, obtaining bachelor or master level degree qualifications. They all stated that constructability was not something they covered during formal education. Participant I-05 stated, "It certainly was not something that came up in my university course. We talked about structural design, and things like project management, and sustainability". The participants identified that designers predominantly gained their knowledge through construction site experience, particularly associated with secondments to site during early career. Participant I-15 when asked how constructability knowledge was gained stated, "the most direct form would be when you are standing on-site with a foreman shouting at you, 'How the +*#% am I supposed to build this?'".

With knowledge being limited to on-the-job experience and predominantly gained during the early career, there appears to be a potential issue with the constructability knowledge of designers within the design office. This was also found by [29] which identified a concern of the level of designer knowledge of practicalities of construction on site.

4.3 Barriers to Implementation of Constructability

4.3.1 Procurement

Nine out of 20 participants identified that reduced consultant and designer fees were a barrier to constructability implementation, constraining the design scope. Participant I-04 said, "where the fees are competitively low, the design team are not able to explore it in as much detail as maybe they would, or should,". Furthermore, while participants recognised that there were benefits of constructability to add value to the design and project, they stated it was hard to tender on them competitively. Participant I-04 noted, "I think the client's got to be willing to understand the value of that and pay for it. But yeah, everything has a cost and you either pay for it upfront or you pay for it later". Participant I-01 stated, "I think we have a little bit of a habit of perhaps, as designers, maybe being a touch conservative or not thinking through how it is going to be built. Moreover, clients were also identified as not wanting to try new approaches, "people do not like doing things in a new way" (Participant I-18). This constrains the potential for innovation within the design process and the adoption of new and improved construction methods. Fee constraints were also seen in the literature [24, 29].

Another barrier several participants noted was that clients did not understand the complexity of construction projects. Participant I-18 stated, "the level of complexity that our industry delivers is not fully understood by, properly understood, by clients".

This resulted in procurement strategies and methods that constrained the design process and reduced the scope of incorporating constructability approaches.

4.3.2 Design and Construction Separation

During the interviews, seven out of the 20 participants specifically mentioned the separation between designers and contractors in the context of a barrier. The construction industry has long known that the separation of designers and contractors leads to issues [11, 21]. Previous studies looking at constructability have shown that co-ordination between disciplines and lack of open communication were barriers [24, 29].

It was noted by Participant I-04 that the specific practice of the separation of permanent and temporary works into the silos of designers and contractors was increasingly becoming a limiting factor in projects, stating "that the permanent works and the temporary works and the construction staging really needs to be considered as one unified element and you cannot really separate them out". In addition to the loss of synergy between permanent and temporary designs, separating designers and contractors leads to potential distrust, with one participant commenting, "it is hard to know what is really an issue and what is just preference engineering" (Participant I-14), when talking about discussions with contractors during projects.

4.3.3 Lack of Education

Education as a barrier to constructability was mentioned by 15 out of 20 participants; it was discussed in two aspects. The first relates to the skill shortage the construction industry is facing, namely an ageing workforce and the second, access to continuing education and training.

With an ageing workforce, there is potential for crucial knowledge and experience to be lost through retirement, and challenges regarding the development of young designers to replace them. Participant I-01 commented that the retirement of senior designers, who tend to have a more varied background, was starting to be noticed, saying "we're almost on a bit of a cliff edge where we're going to be losing many people with a lot of excellent knowledge and experience, who have kind of had that broader career". This issue is compounded by the challenge of getting young designers field experience. Participant I-13 stated, "I think probably it's up to companies to drive that as much as the professional organisations. If we want to have engineers in your office that understand constructability, then we send them to site, and we know that is the best way to do it". Another interesting point raised was the industry's focus on getting site placements for junior or young designers, and not for experienced or older staff. This leads to the design office falling behind on the latest developments on the construction practices in the leadership roles within the design team. Participant I-15 commented concerning senior designers that "there is nothing that necessarily dictates that you ever need to go to a construction site again".

The second education barrier identified was access to information and training for practising designers on the topic of construction. Participant I-18 commented on the absence of training available, “You don’t see many training courses for it”.

5 Conclusions

The main aim of this study was to investigate current practice in the UK construction industry for incorporating constructability within the design phase. To address an observed gap in the literature, and thus expand the body of knowledge, this exploratory research carried out 20 semi-structured interviews. Because of the small sample, caution should be taken in interpreting the results presented below to the broader population, but they do provide a good insight into constructability thinking in the UK.

The research found that typical current practice did not involve any formal procedures or policies for the incorporation of constructability within the design process. There were examples of constructability reviews and constructability programmes being used, but these tended to be exceptions. There were no examples of quantitative assessments being used for constructability decisions to make design decisions. Where informal processes were being used, constructability was a design criterion considered by designers and was assessed through design reviews. These subjective decisions were based on the tacit knowledge of the individuals taking part in the design work.

Interviewees indicated that more needs to be done with constructability, however lack of inertia or other barriers interfere. One of the key barriers to increasing constructability in the design process was procurement methods, with impacts such as reduced fees constraining the scope of designers and procurement methods reinforcing designer and contractor silos. There was also an association of constructability with CDM health and safety considerations, which most likely limits its implementation.

If the construction industry is to have a greater focus on constructability within the design process, formal procedures and policies must be more widely adopted. In addition to this, it would be recommended to increase the use of quantitative assessments in considering constructability, to allow objective design decisions to be made. The industry needs to look at the barriers associated with knowledge and education. The current processes are reliant on tacit knowledge, through constructability reviews and constructability programmes. However, with the impending challenge of the skills shortages facing the construction industry, this must be addressed to prevent design deterioration.

For the UK construction industry to improve its productivity, better incorporation of constructability within the design phase is key to unlocking productivity improvements. The changes the industry is going through, such as digital transformation and a push to modularise, provide an opportunity to incorporate constructability within the design process.

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Analysis of Concurrent Delays in the Construction Industry

A. Samer Ezeldin and Yasmin El-Hakim

1 Introduction

The construction industry has a major role in the development process for any country. It provides necessary infrastructure and services for both public and private sectors. The industry provides, as well, different direct and indirect employment opportunities for skilled and unskilled labors. Therefore, it influences the economic status of the country [16]. The success of any construction project depends on how balanced it is in terms of time, cost and quality. Therefore, managing the project to mitigate delays and their causes is very crucial in construction projects. There are four main categories for construction delays. First category is critical versus non-critical delays. Second category is excusable versus non-excusable delays. Third category is compensable versus non-compensable delays. Forth category is concurrent versus non-concurrent delays [6]. The most controversial type of delays is concurrent delays because there is no unified or agreed upon definition for them. Generally, concurrent delays are two delays happening at the same period of time that different parties are legally responsible for them. Although the previous understanding is the common one among expertise in the industry, experts usually conflict on implementing and construing this definition. Some examples of the reasons of these conflicts are the following. Some experts see that causes of delay events of different parties should overlap in time, while others believe that the effects should overlap even if the causes don't. In addition, some experts think that delay events of different parties have to be within the same analysis period even if they don't overlap in time. However, others see that they have to overlap on time and there are even some experts that believe that they

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have to start and end at the same time [9]. Moreover, there are different approaches of dealing with reimbursement in case of concurrency existence. The first one is that the contractor is entitled for extension of time for the period of concurrency, however, he will not receive any cost compensation. This approach is known as "time but not money". The second approach is apportionment where damages should be apportioned between parties according to each party's liability. Therefore, the contractor is given partial extension of time and partial cost compensation and the owner applies partial liquidated damages on the contractor [13]. Accordingly, in the presence of concurrent delays and the absence of a unified definition, disputes often arise on which party will be responsible for the delay and whether there will be cost compensation or not [3]. Therefore, the following sections discuss how to assess concurrent delays according to the most recognized protocols, different countries laws and standard forms of contracts.

2 Concurrent Delays in Recognized Protocols

2.1 Association for the Advancement of Cost Engineering International Recommended Practice on Schedule Delay-RP29R-03 (AACE [1])

The Association for the Advancement of Cost Engineering International gives two definitions for concurrency. The first one is "two or more delays that take place or overlap during the same period, either of which occurring alone would have affected the ultimate completion date". The second one is "concurrent delays occurs when there are two or more independent causes of delay during the same time period". Therefore, the AACE defines two different theories in regards to concurrency; the first one is the "Literal Theory" where delays have to be "literally concurrent in time" occurring at the same time. Therefore, if they do not start on the same time, they are not concurrent. That is because the first delay that occurs results in a float, so the next delay will not be on the critical path anymore and will not delay the project completion date. However, AACE stated that exact simultaneity is impossible. The second one is the "Functional Theory" where delays should be happening in the same analysis period. Therefore, the selection of evaluation time period for delay analysis may affect the determination of concurrency. So, if the evaluation period has both delays, they are concurrent and if each delay is in different analysis window, they are not concurrent. However, delay causing activities should start near in time for activities to be considered concurrent. That is to eliminate the possibility of taking a big time period as an analysis window [9]. For concurrency to exist, they have to possess different characteristics according to the AACE. These characteristics are: first, that these delays should be unrelated and independent. Second, each delay should delay the project alone even if the other delay does not exist. Therefore, these delays have to be on the critical path of the project when each is studied alone. Third, the delays should be of different parties' responsibilities, but one of them could be a force majeure one. Forth, the delay has to be involuntary. Therefore, pacing delays should not be considered concurrent, because that party has voluntary delayed his work to cope with the slow pace of the work by the other party. Fifth, the delayed work has to be considerable [9]. Hence, that delay should be of impact on the project completion date by a considerable amount. To apply the previous characteristics and theories, it is important to know if the concurrency should be studied once the delay occurred or when the delay affected the project time schedule. According to the AACE, concurrency should be studied consistently with the delay analysis technique that is being used in the project. Therefore, if the delay analysis studies the delays at the time of causation, then concurrency should be studied according to causation. However, if the delays are studied when they affect the schedule, then concurrency should be treated similarly. However, it recommends that concurrent delays to be studied when they affect the schedule [9]. After the existence of concurrency is proved, the AACE considers concurrent delays as excusable non-compensable delays. So, the only remedy is extension of time. That is because each party's right to compensation is offset by the other party's compensation, so no cost compensation is applied [10].

2.2 The Society of Construction Law's Delay and Disruption Protocol (SCL-DDP 2017)

The Society of Construction Law published the delay and disruption protocol to provide guidance when dealing with delay and disruption matters. This protocol was first published in 2002 and then a new edition was released in 2017 which supersedes the 1st edition [14]. The Society of Construction Law's Delay and Disruption Protocol defines concurrency as follows "True concurrent delay is the occurrence of two or more delay events at the same time, one an employer Risk Event, the other a contractor Risk Event and the effects of which are felt at the same time. True concurrent delay will be a rare occurrence". Therefore, the SCL protocol adopts the literal concurrency theory that was elaborated by the AACE. In order for delays to be considered concurrent, they have to start and end on the same time period, not just overlap on time. Moreover, in order for the delays to be studied and to be considered concurrent, they should critically affect the completion date of the project. Therefore, these delays have to be on the project's critical path, so the CPM analysis is important to concurrency analysis. In order to apply the SCL theory, it is important to understand if these delays should be studied at the time of occurrence or when they affect the project time schedule. Therefore, according to the SCL if the effects of the delays are felt at the same time, they could be considered concurrent even if the delays happened at different times. As such, concurrent delays should be assessed when their effect on the project appears at the same time, not their cause [9]. Accordingly, concurrency in the SCL protocol is related to the effect of the delay, therefore, it is considered concurrent effect of sequential delay events [7]. After proving that concurrency existed, it is important to study the consequences of that on the different parties in the project. According to Hasan [7], when concurrency is proved, the contractor's concurrent delay shouldn't reduce the due extension of time that should be granted to the contractor as a result of an employer delay. That is because the SCL protocol is following the English law "Prevention Principle" where the employer couldn't take benefit of a situation whose performance has hindered. Therefore, the employer delay event has caused delays to the project finish date concurrently with the contractor's delay, so, he shouldn't take advantage of his delays. According to El Nemr [5], in order for the prevention principle to be applied in case of concurrency, the contractor has to prove that he couldn't finish in the specified completion date because of the employer's delays. In addition, these delays have to be actual delays not expected or potential ones (Baily 2011 as cited by El Nemr [5]). According to the SCL, if concurrency is proved and the contractor has incurred additional costs because of the employer's delays, then the contractor should be entitled to cost compensation if it is possible to distinguish the costs caused by the employer delays from the costs caused by the contractor's delays. However, if the contractor incurred costs because of his delays, he will not be granted any additional costs. Therefore, in most times, the contractor could only be cost compensated in case the employer delays exceed the contractor's delays in duration [14].

2.3 The American Society of Civil Engineers Standard Guideline for Schedule Delay Analysis [4]

The schedule delay analysis standard committee of the construction institute of the ASCE published the schedule delay analysis in 2016 (ASCE library). This standard provides best principles related to schedule delay analysis with commentary on each principal explaining its reasoning and application (ASCE library). The ASCE Standard Guidelines for Schedule Delay Analysis defines the concurrent delay as a "situation where two or more critical delays are occurring at the same time during all or portion of the delay time frame in which the delays are occurring" (ASCE [4] as cited by Livengood [9]). Accordingly, the delays should overlap, but they don't have to start and end on the same time. However, if delays are separated in time, they are not considered concurrent. In order for delays to be studied and analyzed, they should affect the project's completion date, so they have to be on the critical path of the project. In order to apply the ASCE standard, it is important to know if concurrency should be studied on the time of occurrence or when they affect the schedule. According to Livengood [9], the ASCE standard did not directly mention if concurrency should be considered when it first initiated or when it has an effect. However, he believes that the language of the ASCE guide infers that it should be considered when it is felt. After proving that concurrency existed, the ASCE standard considers concurrent delays as excusable non-compensable delays. Therefore, an extension of time is granted, but no cost compensation to either party. The contractor will not be cost compensated for a delay that is concurrent with an owner delay if it is difficult to apportion delays according to responsibility and damage. Similarly, the owner will not be granted liquidated damages for a delay that is concurrent with a contractor delay of equal time if it is hard to be apportioned. However, if apportionment of concurrent delays according to responsibility and damage is possible, it should be applied [4].

3 Concurrent Delays in Different Countries' Laws

3.1 Concurrent Delays in Egyptian Law

Egypt follows the civil law system where courts apply the codes and principles stated in the law. According to Pejovic [12], the courts have to apply and interpret the laws and principles existed in the code to each case facts. Therefore, if there is a specific case that is not clearly addressed in the civil code, the courts should apply the general principles stated in the civil code trying to fill in the gaps. There is no direct article in Egyptian Civil Law (Law 131 for year 1948) regarding the concurrent delays and there is no judicial authority or persuasive commentary on this topic according to many researchers in that topic. However, some of the Civil Law articles can be construed to help in case of concurrency appearance. Al-Sanhoury- who is a legal scholar who drafted the Egyptian civil code 1948 and published a book called "El-Waseet" to explain the civil code in details- in his book El Waseet (as cited by El Nemr [5]) defined "the contributory Fault" as a fault where each party has an independent contribution to the harm caused. In addition, according to El Nemr [5] this concept is the most relevant one in the Egyptian Civil Code to the concurrent delays. This concept was derived from **article 169** in the Civil Code which states that *"When several persons are responsible for damage, they are jointly and severally responsible to make reparation for the damage. The liability will be shared equally between them, unless the judge fixes their individual share in the damage due"*. Moreover, Al Sanhoury (as cited by El Nemr [5]) refers as well to **article 216** in Egyptian Civil Code as a specific article that addresses the concept of contributory fault. This article stipulates that "*The judge may reduce the amount of damages or may even refuse to allow damages if the creditor, by his own fault, has contributed to the cause of, or increased, the loss"*. Therefore, Al Sanhoury (as cited by El Nemr) concluded that these two articles no 169 and 216 allow the judge to apportion damages between the parties where each party bears his share of the harm. However, if it is hard to allocate each party's share of the harm, the judge may assume equal responsibility and share for each one.

3.2 Concurrent Delays in English Law

England follows the common law system where the previous judicial decisions should be followed in the following cases. Therefore, courts have a major role in creating the law. Accordingly, the lawyer in common law systems compares his actual case with previous cases having similar legal issues. Then, from these similarities, he derives the binding legal rule in his case [12]. According to Hughes et al. [8], the concurrent delay definition that is widely accepted in England was proposed by John Marrin in 2002 as "*concurrent delay is used to denote a period of project overrun which caused by two or more effective causes of delay which are of approximately equal causative potency*". Therefore, according to John Hughes, Andrew Agapiou, John Blackie based on that definition, the effective causes of delay have to be the responsibility of both the employer and the contractor. However, the causes of that delay do not have to be concurrent in time, but they have to affect the project completion date equally. Therefore, if concurrency existed with equal causative potency, the contractor will be entitled extension of time for the concurrent delay, but no cost compensation, and that could be referred to as the "Malmaison Approach". That approach was first used in 1999 in case of Henry Boot v Malmaison and then used in subsequent cases [8]. In that approach, the contractor is granted full extension of time for the period of delay that was caused concurrently by employer and contractor responsible events if one of these events was a relevant event and these events have equal causative potency regardless of the contractor's own delays. That could be justified by two reasons, the first is that denying the contractor entitlement for extension of time could be regarded as an act of prevention. The second reason is that according to the JCT contract, the contractor is entitled to extension of time in case of a relevant event without mentioning any clauses related to concurrency or denial of extension of time in case of concurrency. However, the contractor is not entitled to cost compensation because he would have incurred the same loss and expenses anyway because of the delays he is responsible for [8]. On the other hand, if the effective causes of delay do not have "approximate equal causative potency", the event that has a higher causative potency should be regarded as the dominant cause. According to Arif and Morad, the dominant cause type of analysis is a more logical approach instead of taking the occurring time as the determining factor because the dominant cause of all concurrent delays will be the one to be studied. In that approach, the dominant cause of delay is the one responsible for the delay in case of concurrency [10]. However, according to Marrin as cited by to Hughes et al. [8], there is doubt in dealing with that concept because of lack of judicial support. There are other approaches to analyze concurrency, such as the "But For" and the "First in line" analysis; however, among all these approaches, the most widely used ones in English courts are the Malmaison approach and the dominant cause approach. According to Abdalall [2], the Malmaison approach is considered the established law in case of concurrent delays in England.

3.3 Concurrent Delays in US Law

USA follows the common law system similar to England. However, it has different approaches and cases while dealing with concurrency. According to Long [10], US courts have three main approaches for dealing with concurrent delays. These approaches are time but no money, apportionment or responsibility based on critical path delay analysis. The first approach "time but no money" dated back to early 1900s where time extension was granted in case of concurrency but no cost compensation. This approach sometimes referred to as "Easy rule" in which neither compensation nor apportionment is applied [3]. And according to Arif and Morad, this approach is regarded by the courts as "Doctrine of concurrent delays". It is usually used when apportionment could not be done accurately or because of lack of evidence to prove each party's responsibility. After that, according to Long [10], this approach was abandoned and the apportionment approach takes place to have more lenient way of dealing with concurrency. This approach is also referred to as "Fair Rule" or "comparative negligence" as mentioned by Arif and Morad. However, evidence and proof should be present of the responsibility of each party to the damage in order for the courts to be able to apportion costs between parties. If that segregation of responsibilities is difficult to be attained, apportionment will not be used. Therefore, according to Long [10], critical path delay analysis could be used as a good alternative to apportionment as it gives good evidence of cause and effect of delays in the project's time schedule. Arif and Morad have also highlighted the importance of that approach in providing proof and solid ground for analyzing concurrent delays. USA has a better experience in dealing with concurrency according to Arif and Morad among other countries using common law system. Therefore, it could be considered as a benchmark. Therefore, the main principles used in US Law were summarized by Bramble and Callahan 2000 (as cited by Arif and Morad [3]) as follows. First, Calculations for time and cost should be provided by the involved parties in order to analyze concurrent delays. Second, the burden of proof lies on the party claiming financial recovery. Third, contractor will be awarded time extension if there is a third party that is involved in causing delays. Forth, if concurrent delays are excusable and non-compensable, time extension is only granted. However, if both delays are compensable, compensation will be given due to one delay only.

4 Concurrent Delays in Standard Forms of Contracts

4.1 Concurrent Delays in FIDIC 2017

FIDIC is a widely accepted and used standard form of contract worldwide. In Egypt, FIDIC is widely used in public and private sectors because there is no Egyptian standard form of construction contracts. In the older version of FIDIC, there was no specific clause for dealing with concurrency occurrence. It only included a mechanism of dealing with delays in terms of time extension and cost compensation [2]. However, According to Mangan [11], the new version of FIDIC 2017 suggested that parties should agree on the set of rules while analyzing concurrency. FIDIC suggested in the guidance to the general conditions, that the parties agree on the approach that they are going to use in case of concurrency. In addition, it mentioned that the use of SCL protocol become more widely accepted among organizations. In Clause 8.5 in FIDIC 2017 "Extension of time for completion", it is mentioned the cases under which the contractor is entitled for extension of time and how that should be assessed. Then, it was mentioned "If a delay caused by a matter which is the employer's responsibility is concurrent with a delay caused by a matter which is the contractor's responsibility, the contractor's entitlement to EOT shall be assessed in accordance with the rules and procedures stated in the Special Provisions (if not stated, as appropriate taking due regard of all relevant circumstances)" (FIDIC 2017).

4.2 Concurrent Delays in NEC 3

This standard type of contract is widely used in UK as it is recommended by the government to be used for public construction projects. NEC3 is the new version of NEC that replaced the older versions [2]. NEC3 doesn't have any clauses regarding the concurrent delay occurrence and remedy. It only gives a technique for evaluating extension of time and cost compensation (Lowsley and Sadler 2012 as cited by Abdalall [2]).

5 Model Development

This paper presents an analytical model that is user friendly and covers several computational technics, using MS Excel Visual basic. That specific programming language is used because it provides wide array of functions, allows for macro recording, it is easy to be used and has many available online tutorials. It also allows for building comprehensive models. The model is based on the following incremental methodology:

1. Creating baseline schedule based on the critical path method
2. Creating update schedule based on critical path method
3. Creating delay analysis based on time impact analysis method
4. Creating owner responsible delays schedule based on actual dates for owner activities and as sequence dates for contractor activities to see the effect of owner delays only on the schedule

5. Creating contractor responsible delays schedule based on actual dates for contractor activities and as sequence dated for owner activities to see the effect of contractor delays only on the schedule
6. Clarifying if concurrency exist based on the concurrency approach selected by the user
7. Clarifying where concurrency exist, which activities that have contractor responsible critical delays is concurrent with which activities that have owner responsible critical delays
8. The final output will be the extension of time that should be granted to the contractor and the number of concurrent days.

5.1 Model Interface and Initial Testing

The model consists of 8 sheets as presented below. Each sheet is illustrated and has a screen for its final output after its illustration (Fig. 1).

- Start: This is the start sheet where the user inputs the basic information about his project; including: name of the project, contractor name and project budget value. In addition, the user will choose which concurrency approach he is going to use (i.e.: SCL protocol, AACE, ASCE).
- Schedule: In this sheet, the model user inputs the activity IDs, activity names, durations and responsibility for each activity. Then, the model will ask for the number of predecessors and number of successors. After that, the model will insert columns for the number of predecessors, lag, relationships (will be equal to the number of predecessors) and number of successors according to the user inputs. Then, the model will ask the user to insert the predecessors, lag and relationship

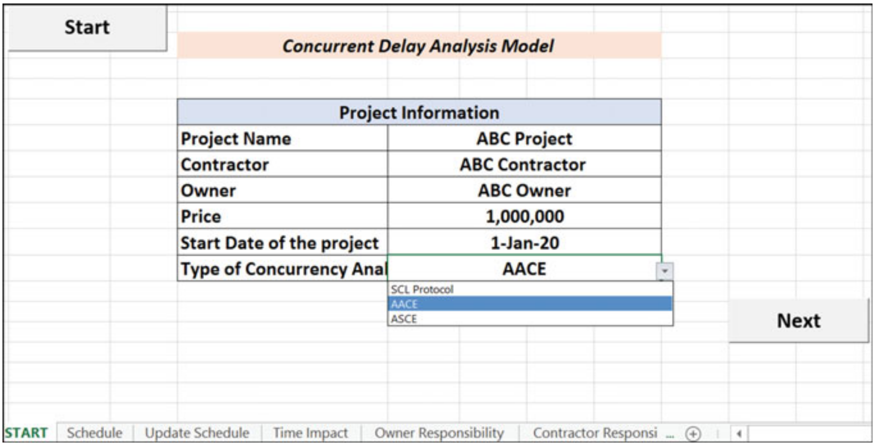

Fig. 1 Start sheet, insert your project data

between each activity and its predecessors. After that, the model will output the successors' name the early start and early finish dates and late start and late finish dates and the total float (Fig. 2).

- Update Schedule: In this sheet, the model will ask the user to insert any new activities and insert the new number of predecessors, new number of successors, the relationships and lags for the new activities. Then, the model will define the new successors. After that, the model will ask the user to insert the actual data, and the data date. Then, the model will run the updated schedule and will output the start and finish dates for each activity (Fig. 3).
- Time Impact Analysis: In this sheet, the model will ask the user to insert the subset of activities related to his claim delay events, the new number of predecessors, new number of successors, relationships and lags. Then, the model will define the new successors. After that, the model will ask the user to insert the actual data, and the data date. Then, the model will run the time impact analysis and will output the start and finish dates for each activity (Fig. 4).
- Owner Responsibility: In this sheet, the model will run the owner responsible delays only to give the finish date of the project according to the owner responsibility delays only. In addition, the model will output the late dates and the total float.
- Contractor Responsibility: In this sheet, the model will run the contractor responsible delays only to give the finish date of the project according to the contractor responsible delays only. In addition, the model will out put the late dates and the total float
- Analysis: In this sheet, the model will run the concurrency analysis based on the selected approach in the first sheet "Start". The model will show which critical

Insert Data | New Schedule | Identify Successors | Run Baseline Schedule | Draw Barchart | Clear All | Next

Baseline Schedule

activity ID	Activity Name	Duration (Days)	Responsibility	Predecessor1	Predecessor2	Lag1	Lag2	Relationship1	Relationship2	Successor1	Successor2	Early Start	Early Finish	Late Start	Late Finish	Total Float
A	Start	0	contractor					FS	FS	D	E	01-Jan-2020	01-Jan-2020	01-Jan-2020	01-Jan-2020	0
B	BBB	2	contractor	E	D			FS	FS	C		07-Jan-2020	09-Jan-2020	07-Jan-2020	09-Jan-2020	0
D	DDD	4	owner	A				FS	FS	G	B	02-Jan-2020	06-Jan-2020	02-Jan-2020	06-Jan-2020	0
E	EEE	2	contractor	A				FS		B		02-Jan-2020	04-Jan-2020	04-Jan-2020	06-Jan-2020	2
G	GGG	1	owner	D				FS		C		07-Jan-2020	08-Jan-2020	08-Jan-2020	09-Jan-2020	1
C	End	0	contractor	B	G			FS	FS			10-Jan-2020	10-Jan-2020	10-Jan-2020	10-Jan-2020	0

Fig. 2 Baseline schedule sheet

Insert Actual New Activities & Relations | Define New Successors | Insert Actual Dates | Run Updated Schedule | Draw Barchart | Clear All | Next

Update Schedule

ctivity ID	Activity Name	Duration (Days)	Responsibility	Predecessor 1	Predecessor 2	Lag1	Lag2	Relationship1	Relationship2	Successor1	Successor2	Actual Start	Actual Finish	%complete	New Early Start	New Early Finish
A	Start	0	contractor					FS	FS	D	E	01-Jan-2020	01-Jan-2020	100%	01-Jan-2020	01-Jan-2020
B	BBB	2	contractor	E	D			FS	FS	C		08-Jan-2020	11-Jan-2020	100%	08-Jan-2020	11-Jan-2020
D	DDD	4	owner	A				FS	FS	G	B	04-Jan-2020	10-Jan-2020	100%	04-Jan-2020	10-Jan-2020
E	EEE	[illegible]	contractor	A				FS		B					10-Jan-2020	12-Jan-2020
G	GGG	1	owner	D				FS		C					11-Jan-2020	12-Jan-2020
C	End	0	contractor	B	G			FS	FS						13-Jan-2020	13-Jan-2020

Fig. 3 Update schedule sheet, data date = 10th Jan 2020

Insert New Data | Run Time Impact Analysis | Draw Barchart | Clear All | Next

Time Impact Analysis

activity ID	Activity Name	Duration (Days)	Responsibility	Predecessor1	Predecessor2	Predecessor3	Lag1	Lag2	Lag3	Relationship1	Relationship2	Relationship3	Successor1	Successor2	Successor3	Successor4	Actual Start	Actual Finish	%complete	New Early Start	New Early Finish
A	Start	0	contractor							FS	FS		D	E	F	H	01-Jan-2020	01-Jan-2020	100%	01-Jan-2020	01-Jan-2020
B	BBB	2	contractor	E	D					FS	FS		C				08-Jan-2020	11-Jan-2020	100%	08-Jan-2020	11-Jan-2020
D	DDD	4	owner	A						FS	FS		G	B			04-Jan-2020	10-Jan-2020	100%	04-Jan-2020	10-Jan-2020
E	EEE	2	contractor	A						FS			B							10-Jan-2020	12-Jan-2020
G	GGG	1	owner	D	I	F				FS	FS	FS	C							17-Jan-2020	18-Jan-2020
F	FFF	1	owner	A						FS			G							10-Jan-2020	11-Jan-2020
H	HHH	2	owner	A						FS			I							10-Jan-2020	12-Jan-2020
I	III	3	owner	H						FS			G	C						13-Jan-2020	16-Jan-2020
C	End	0	contractor	B	G	I				FS	FS									19-Jan-2020	19-Jan-2020

Fig. 4 Time impact sheet, data date = 10th Jan 2020, new activities: F, H&I

activities that have owner responsible delays are concurrent with which critical activities that have contractor responsibility (Fig. 5).

- Final Result: In this sheet, the model will output based on the previous sheets; the total delay, concurrent delay, contractor responsible delays, owner responsible delay and extension of time granted to the contractor (Fig. 6).

Analyze Concurrency | Clear All | Next

Owner Responsibility

activity ID	Activity Name	Start	Finish	BL Start	BL Finish	Start of Delay	End of Delay	Concurrent Activities	
G	GGG	17-Jan-2020	18-Jan-2020	07-Jan-2020	08-Jan-2020	08-Jan-2020	18-Jan-2020	B	C
H	HHH	10-Jan-2020	12-Jan-2020						
I	III	13-Jan-2020	16-Jan-2020						
C	End	19-Jan-2020	19-Jan-2020	10-Jan-2020	10-Jan-2020	10-Jan-2020	19-Jan-2020	B	C

Contractor Responsibility

activity ID	Activity Name	Start	Finish	BL Start	BL Finish	Start of Delay	End of Delay	Concurrent Activities	
B	BBB	08-Jan-2020	11-Jan-2020	07-Jan-2020	09-Jan-2020	09-Jan-2020	11-Jan-2020	G	C
C	End	12-Jan-2020	12-Jan-2020	10-Jan-2020	10-Jan-2020	10-Jan-2020	12-Jan-2020	G	C

There is Concurrency

Fig. 5 Analysis sheet

Final Result

Your Approach for Concurrency Analysis	AACE	
Baseline Project Finish Date	10-Jan-2020	
Update Finish Date	13-Jan-2020	
Time Impact Finish Date	19-Jan-2020	
Total Delay	9	
Concurrent Delay	There is Concurrency	2
Contractor is Responsible for a Delay of	0	
Owner is Responsible for a Delay of	7	
Extension of time Granted to Contractor	9	

Fig. 6 Final result sheet

5.2 Model Validation

In this section, the model is tested using actual project data. The project used for verification is a well-known hospital located in Cairo, Egypt. The building is composed of 2 towers; the first one is a hospital and the second one is medical clinics. The building is composed of 8 floors and 3 basements. The building capacity is 158 beds, 5 operating theatres and 220 Medical offices. The scope of the contract under consideration is the Architectural and MEP package. The contract between the Owner and the Contractor is following FIDIC 1987 and it is a unit price contract. The contract price was 371,273,986 EGP. The commencement date for the project was 3rd of November 2013 and the agreed upon finish date was 3rd of September 2015 with a contract duration of 670 days. The work on the hospital was delayed and the Contractor sent a claim asking for extension of time and cost reimbursement. The claim included 3 main events which are:

- 26th Feb 2014: Major imposed Architectural and MEP design modifications
- 15th May 2014: Major imposed Electrical design modifications
- 19th May 2014: Major imposed Arch design modifications.

The Contractor claimed that he is delayed 109 days due to the Owner design modifications that affected most of his work shifting the project completion date from 3rd of September 2015 to 21st December 2015, so he is claiming extension of time for that period of time. In addition, he claimed cost reimbursement equals to 19,451,341 EGP. However, the Consultant representing the Owner had a counter claim in which he rejected the first two events claiming that the design modifications sent in these dates were minor; in addition, he claimed that the Contractor was already delayed in his work beyond the Owner responsibility. The Consultant has accepted only the third event and accepted to give the Contractor an extension of time of 63 days due to that event. However, due to concurrent delays, the Contractor will not be granted cost reimbursement. In response, the Contractor rejected the Consultant's counter claim and insisted on his claim for both time and cost compensation. In addition, he said that according to the SCL protocol, there is no proved concurrency in the project and the Contractor's delays were due to Owner's continuous design modifications. It is worth to highlight that the contract didn't specify any approach to deal with concurrent delays. In addition, the Consultant didn't specify according to which theory he is deriving his conclusions. Therefore, the aim of this section is to input project data into the model and compare the output result to both the Contractor's claim, and the Consultant's counter claim. After that, the researchers' reflections on both will be highlighted. As mentioned before, the model is composed of 8 sheets; the second and third sheets outputs namely "Schedule" and "Update Schedule" will be compared to the project primavera schedule to prove that the model is running accurately and is giving the same results. Because the model is based on calendar days, the primavera schedule was first run as calendar days as well, so the project baseline finish date becomes 10 May 2015. The following are inputs to the model, number of activities inputted are 2850, max number of predecessors is 60 and the max number of successors is 102. The model gives an accurate result in both the baseline and updated schedule in all activities with a small difference in project finish date when compared to the primavera schedule of 6 and 5 days respectively. That difference could be justified as follows. The finish to start relationship in the model was based on that the activity will start on the following day after the preceding activity finishes. However, in primavera, some activities follow the same logic, while others start on the same day because in primavera the time unit is hour, so once the activity finishes in terms of hours, the succeeding one will start. Therefore, that small difference is neglected. After proving that the model could run the sequence of the activities accurately and give valid accurate results, the rest of the sheets are run based on the same logic. Then, the final result is compared to the Contractor's and Consultant's claim. The three events were put in the model. Then, we analyzed the result according to each technic; namely, AACE, SCL protocol and ASCE. The Owner delays in the three events were the dominant cause of delay leading to a project completion date later than that of the Contractor responsible delays. Hence, the model gives the following results. According to the SCL protocol, there is no concurrency. Therefore, the Contractor should be granted an extension of time equals to the whole delay period because the Owner delays were the dominant ones. In addition, the Contractor should be compensated normally according to the Owner delays. However, in case of AACE and ASCE, the concurrency is proved. Therefore, the Contractor should be granted extension of time equals to the value of concurrent days plus the Owner responsible delays. However, for cost compensation, according to the AACE, he will not be compensated for the concurrent delays. In case of the ASCE, the Contractor will be granted extension of time only except if he could separate his responsibility from the Owner's responsibility in the concurrent delays with supported evidence. In this case, apportionment could be applied. Figures 7, 8 and 9 show the model cumulative effect of the three events according to the three technics.

Final Result

Your Approach for Concurrency Analysis	AACE	
Baseline Project Finish Date	16-May-2015	
Update Finish Date	16-Sep-2015	
Time Impact Finish Date	06-Oct-2015	
Total Delay	143	
Concurrent Delay	There is Concurrency	79
Contractor is Responsible for a Delay of	0	
Owner is Responsible for a Delay of	64	
Extension of time Granted to Contractor	143	

Fig. 7 Cumulative result for the 3 events based on the AACE

Final Result

Your Approach for Concurrency Analysis	SCL Protocol
Baseline Project Finish Date	16-May-2015
Update Finish Date	16-Sep-2015
Time Impact Finish Date	06-Oct-2015
Total Delay	143
Concurrent Delay	There is No Concurrency
Contractor is Responsible for a Delay of	79
Owner is Responsible for a Delay of	143
Extension of time Granted to Contractor	143

Fig. 8 Cumulative result for the 3 events based on the SCL protocol

Final Result

Your Approach for Concurrency Analysis	ASCE	
Baseline Project Finish Date	16-May-2015	
Update Finish Date	16-Sep-2015	
Time Impact Finish Date	06-Oct-2015	
Total Delay	143	
Concurrent Delay	There is Concurrency	79
Contractor is Responsible for a Delay of	0	
Owner is Responsible for a Delay of	64	
Extension of time Granted to Contractor	143	

Fig. 9 Cumulative result for the 3 events based on the ASCE

From the previous results, the model recommends an extension of time of 143 days which is closer to the Contractor's claim of 109 days. The model gives a larger extension of time because of the following:

- Lack of information: the exact impact of the design modifications was not available. For example, one of the modifications was related to modification of gypsum partitions in floors B1, 1st, 5th, 6th and 7th floors. It was not clear to which zone that modifications applies and to what extent, if it is a 100% re do of the work or partial modifications. Therefore, the modifications were linked to these floors general gypsum partitions activity as if these modifications will 100% affect them which may be different from the real situation.
- The fragnet activities (which are the new activities that are added to the schedule to represent the effect of claim events) and their durations were assumed. These assumptions may be different from those assumed by the Contractor. For example, it was assumed that the modification of gypsum partitions in each floor will require

submittal of new shop drawings for gypsum partitions with a duration of 18 days, the approval for them will take 15 days and the removal of any abortive work will take 7 days. The Contractor may have assumed different activities and different durations.

However, in general the Contractor's claim seems to be more valid and is supported with proofs especially in the concurrency issue. The Contractor mentioned the approach he used to prove if there is concurrency or not and highlighted that the concurrency should be studied for critical path only. He proved that there is no concurrency according to the SCL protocol which matched the model result based on that technic. On the other hand, the Consultant didn't specify the approach that he used in analyzing concurrency. In addition, he highlighted Contractor delays in some non-critical activities while referring to concurrency which is not compatible with any concurrency approach. Accordingly, that emphasizes the importance of the model used in this research, as it will guide the user into the main steps that he should follow during analyzing concurrency. In addition, it will give him the opportunity to choose the technic he is using for concurrency to be able to prove and get valid and accurate results.

6 Conclusion

In conclusion, the model proposed in this paper could be a useful tool for concurrency analysis in any project. It gives the user the opportunity to choose one of the well-recognized technics for concurrency analysis; namely AACE, SCL Protocol and ASCE. The user should input the basic data for the project into the model, namely; the activities names, durations, predecessors, relationships and responsibility for each activity. In addition, the user should input the updated data for the project in the Update schedule and Time impact sheets. The model would, then, identify successors and output dates accordingly. Moreover, the model would run the owner delays and the contractor delays, separately to analyze each party's responsible delays. After that, the model would run the concurrency analysis highlighting where the concurrent activities are. Finally, the model would output each party's responsibility and the extension of time that should be granted to the contractor. The model is verified using actual project data which is a well-known hospital in Egypt to evaluate its accuracy. For that project, the model results were closer to the Contractor's claim than that of the Consultant's because in the Contractor's claim, it was clear the approach he used while analyzing concurrency and his claim was supported with strong evidence; unlike the Consultant's counter claim. Therefore, this model would help its user to analyze concurrency and to support claims with valid evidence. It is recommended that parties to the contract agree from the beginning of the project on the definition of concurrency and the way of dealing with its existence to mitigate disputes resulting from it.

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Current Practices of Calculating and Utilizing Road User Costs in the U.S.

K. J. Shrestha, M. Uddin, and J. Adebiyi

1 Introduction

Ongoing road construction projects cause inconvenience to road users as some or all lanes may be closed during construction, and road users will need to slow down, take a detour, or wait in the queue to pass the construction work zones. To reduce such inconvenience, construction is sometimes scheduled at nighttime or over the weekends. The rationale is that during nighttime and weekends, the impact on road users will be less severe, and fewer road users will be affected. Other times, contractors will be incentivized for completing construction earlier than the maximum duration allocated in the contract or penalized for not completing the construction within the allocated duration. These decisions on allowing construction activities only on a certain day of a week, a time interval of a day, or a certain duration depend on the calculated or perceived impact of construction work zones on road users. Several factors such as traffic volume on the road and duration of construction affect such impacts. For example, a shorter duration of construction will be more preferred on roads with higher traffic.

To make consistent decisions on road closures, the impact of the road closure needs to be analyzed and quantified. Such quantification can be expressed in multiple forms such as the number of road users affected the total delay experienced by all road users, or the monetary value of all the impacts. Among these, quantification in terms of monetary value is the most preferred method as such quantification allows the evaluation of multiple design and construction alternatives by adding the construction costs and the impact of a construction work zone on road users. For example, in the A + B contracting method, contractors' bids are evaluated based on the bid amount and the monetary value of the number of days requested for the

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construction. However, while the monetary quantification of the impact is the most preferred method, it is also the most difficult method. The monetary quantification of such impacts is commonly known as the road user cost.

Many studies have been conducted to quantify road user cost since as early as 1986 [5, 18, 21, 26]. Chui and McFarland [5] categorized road user cost into vehicle operating costs, time costs, accident costs, traffic violation costs, and other non-quantifiable costs such as comfort and convenience. In 1985 dollar-value, the value of time was computed as $8.00 per person-hour for drivers and $10.40 per vehicle-hour for passenger cars based on survey data. The earlier studies focused on computing road user cost for benefit cost analysis of new roadway projects. More recently, road user costs are increasingly being used to account for the impact of construction work zones on road users. Additionally, road user cost is used to evaluate bids using various innovative contracting methods, and to provide incentives or disincentives to contractors. Despite these applications of road user costs, there is a lack of nationally accepted methodology to compute road user costs. Many states' Departments of Transportation (DOTs) have developed and implemented their own methodologies to compute road user costs while some do not compute road user costs at all or do not compute the road user costs in-house. For such state DOTs the understanding of the current methodologies of calculating road user costs in order to develop their own methods can be beneficial. This study reviewed the current practices of calculating road user costs from multiple state DOTs from existing literature and conducted a nationwide survey to compare the current and perceived factors related to road user cost calculation methodologies.

2 Prior Studies

The Federal Highway Administration (FHWA) [10] requires states to "implement a policy for the systematic consideration and management of work zone impacts on all Federal-aid highway projects …throughout the various stages of the project development and implementation process" and encourages states to implement such policy for non-Federal-aid projects as well. The road user cost quantifies such impact of construction work zones in monetary values. The road user cost has traditionally been associated with various benefit cost analysis of new construction projects [4, 5, 11, 16, 17]. National Cooperative Highway Research Programme (NCHRP) Synthesis 494, entitled *Life-Cycle Cost Analysis for Management of Highway Assets*, states that the inclusion of road user costs when comparing alternative projects is "one of the great advances in public-sector infrastructure management and decision making" [11]. Lee et al. [17] argue that road user costs are essential components of life cycle cost analysis.

Over time, as the U.S. shifted its focus from the construction of new infrastructure to the improvement of existing infrastructure, the importance of road user cost in construction management decision making is increasingly being realized [7–9, 13, 14, 18, 20, 25, 26]. Overall, the road user cost is used for multiple decision making including the evaluation of bids in innovative contracting methods such as evaluating A + B bidding, determining incentives and disincentives to contractors for early and late completion of construction; accelerating construction projects; determining the lane occupancy change for work-zone lane closure outside approved hours; and conducting life cycle cost analysis.

Despite the importance of the road user costs, prior studies have revealed that many state DOTs do not have well-developed methodologies for calculating road user costs, have outdated calculation methodologies, have relied mostly on engineering judgement, or have varied methodology within the same DOT [21, 30]. Further, prior studies have focused on comparing the methodologies used within a single state or states in a specific region. A national level survey of state DOT practices of calculating and utilizing road user costs will provide a better understanding of the topic. The findings of this survey can be used to develop a better road user cost calculation methodology, which will ensure more effective contracting decision-makings in the future.

2.1 Existing Road User Cost Calculation Methodologies

FHWA and many state DOTs have developed their own methodologies to compute road user costs. The FHWA report *Work Zone Road User Costs: Concepts and Applications* is one of the most comprehensive resources on this topic [18]. The report categorizes the road user costs into monetized and other impacts. Monetized impacts include (a) travel delay costs, (b) vehicle operating costs, (c) crash costs, (d) emission costs, and (e) impacts of nearby projects. The first three components of monetized impacts have been included in most of the earlier studies. Other impacts include (a) noise, (b) business impacts, and (c) inconvenience to local community [18]. These impacts cannot be easily quantified. The various practices of computing monetized road user costs are described below.

2.1.1 Travel Delay Cost

The travel delay cost represents the cost associated with lost opportunity because the road users had to spend more time on the road. Although various methodologies compute travel delay cost differently, the fundamental equation used to calculate travel delay is presented in Eq. (1).

$$\begin{aligned} Travel\ Delay\ Cost &= Delay\ Time\ in\ Hours \\ &\quad * Hourly\ Dollar\ Value\ of\ Delay \end{aligned} \tag{1}$$

The delay time can be calculated for forced-flow (queued) traffic condition or free-flow traffic condition. For example, the Highway Capacity Manual considers various factors such as the number of open lanes, intensity of construction activities, base capacity, and presence of on-ramps to analyze forced-flow traffic conditions to compute travel delay [14, 28]. In an alternative scenario, the travel delay for the free-flow conditions can be computed based on the length of a work zone, speed-limit without work zone, and work-zone speed limit. This travel delay for the vehicles is distributed for different types of vehicles such as passenger cars and trucks based on the historical vehicle composition data. This step to distribute the total delay across various types of vehicles is important as the hourly dollar values associated with delays can vary significantly based on the vehicle type. Further, depending on the vehicle occupancy, purpose of travel (personal or business), and travel details (such as intercity or local), the hourly dollar value of delay can be different. However, none of the state DOTs currently use different hourly dollar value of delay for different locations within the state. The economic conditions within a state can vary widely depending on the location. This affects the construction costs and contractors' bids. As such, the effect of location on the hourly dollar value of delay should be considered for more accurate representation of the road user costs.

2.1.2 Vehicle Operating Costs

The vehicle operating costs include the additional cost associated with the use of vehicles for longer time periods because of the construction work zone. It includes various components such as fuel consumption, tire wear, engine oil consumption, repair and maintenance, and mileage-related depreciations [9, 18]. Factors affecting the vehicle operating costs include detour length, speed, speed changes, and idling time. The fuel cost is the primary cost component of the vehicle operating costs. Several empirical formulas have been developed to link speed, terrain types, and distances with the fuel consumption. Thus, depending on the location of the construction project, prior and current speed limits, and detour lengths, the increase in fuel consumption can be calculated as an additional vehicle operating cost. As detailed information of each vehicle cannot be obtained and used for all the vehicles travelling through construction zones, vehicle operating cost calculation methodology should emphasize accurate estimations of the vehicle operating costs based on the limited information that is easily accessible.

2.1.3 Crash Costs

In 2018, 755 fatalities occurred in construction work zones (American Road and Transportation Builders Association (ATBA) [3]). Some studies, such as Mishra et al. [19], have analyzed crashes in construction work zones to understand the various factors associated with crashes in construction work zones. The evaluation of crash costs in construction work zones is important as the likelihood of crashes increases when there is a construction work zone [13]. The direct and indirect costs associated with fatalities, injuries of various severity levels, and property damages are considered as components of the crash costs [15, 18]. The crash costs are calculated based on the increase in the likelihood of crashes and crash severities resulting from the presence of work zones, and the monetary value of each crashes. The likelihood of crashes can be calculated using crash modification factors presented in American Association of State Highway Transportation Officials (AASHTO) Highway Safety Manual [1]. Such crash modification factors need to be calibrated based on historical data [24]. Most of the studies related to crash analysis are focused on crash frequency calculation rather than crash cost calculation. Thus, newer studies should focus on quantifying the monetary impact of the crash costs.

2.1.4 Emission Costs

Compression ignition engine-powered vehicles produces emissions that include particulate matter (PM), NO_x, and CO that have an adverse effect on the climate and human health. Multiple factors, such as vehicle class and weight, driving cycle, fuel type, vehicle age, and terrain affect emission [6, 12, 18]. The increase in idling time, speed changes, and increased travel time are likely to increase emissions. The costs associated with such an increase in emission are included as emission costs. Accurate quantification of the increase in the quantity of emission as well as the unit cost of emission is challenging when a limited amount of data is available. The Motor Vehicle Emission Simulator (MOVES) developed by the U.S. Environmental Protection Agency (EPA) can be used to estimate emissions [29]. Utilizing tools such as MOVES that require a large amount of project-specific data may not be practical for the road user cost calculation. As such, simplified emission cost calculation methodologies need to be developed to approximate emission costs.

2.1.5 Impacts of Nearby Projects

Ongoing construction projects can affect not only the road users of the same road, but also road users of connected roads nearby [18]. This is the most complicated component of the road user cost and is not often computed by state DOTs.

3 Research Objectives

Many state DOTs and organizations have developed various customized methodologies to compute the road user costs. If a state DOT is planning on developing and implementing a new road user costs calculation methodology or improve an existing one, the understanding of current practices is essential. Several studies in the past have attempted to synthesize the current practices of calculation the road user costs, but either they cover practices within only one state or cover only a few neighboring states. Such studies can provide limited insights about the current practices. Thus, the main goal of this study is to conduct a nationwide questionnaire survey to identify current practices of calculating and utilizing the road user costs.

4 Methodology

This study conducted an extensive review of existing literature on the road user costs. Based on the findings from the review, a survey questionnaire was developed to understand the current practices of calculating and utilizing the road user costs. A pilot study of the survey was conducted with TDOT engineers. Subsequently, the questionnaire was updated to accommodate the feedback from the TDOT representatives. The contact information of all 50 state DOT engineers related to the road user cost was collected by visiting corresponding state DOT websites and/or other relevant websites. The updated questionnaire was distributed to the state DOT engineers via REDCap®, a web-based surveying tool. 36 state DOTs including TDOT completed the survey (74% response rate to date). However, TDOT responses collected during the pilot survey were not included in further analysis. In addition, the partial responses received from three additional state DOTs were not included as they did not include relevant answers.

The survey included questions about the application of road user costs and road user cost calculation methodologies. Most of the questions were in the form of the multi-select, multiple choice, or Likert scale question. In multi-select questions, respondents can choose more than one answers. As such, the sum of percentages of responses can exceed 37 responses or 100%. If some respondents did not select any answer in a specific question, the sum of the total might be less than 37 responses or 100%. The survey did not collect any personal information of the respondents. The East Tennessee State University (ETSU) Institutional Review Board (IRB) determined the study did not meet the definition of research involving human subjects, and hence it did not require the IRB approval.

5 Results

The results of the survey are summarized in this section in two categories: (a) applications of road user costs and (b) road user cost calculation methodologies.

5.1 Applications of Road User Costs

Currently, 34 out of 37 responding state DOTs calculate the road user costs. About three quarter of respondents (70%) calculate the road user cost during bidding and contracting phase, 49% during planning and environmental evaluation phase and

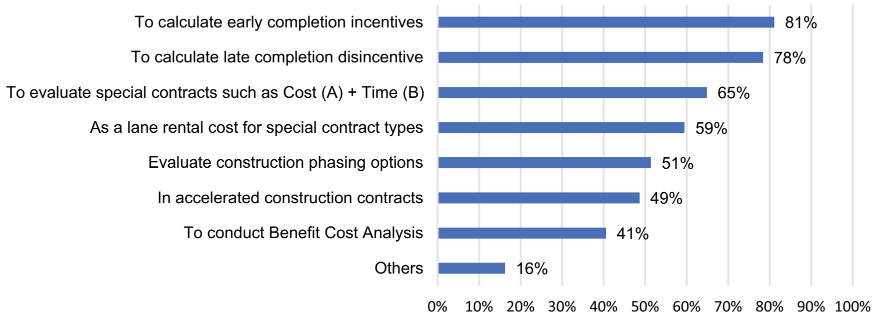

Fig. 1 Road user cost application stage

43% during construction phase. Most of the state DOTs uses the road user cost for early completion incentive (81%) and late completion disincentives (78%) (Fig. 1). Furthermore, more than half of the respondents use the road user cost to evaluate special contracts, and as lane rental cost for lane-closure outside authorized time. About half of the respondents are utilizing the road user costs to evaluate construction phasing option (such as nighttime or weekend construction), to conduct benefit cost analysis, and to accelerate construction contracts. This result on benefit cost analysis aligns with the finding from a previous study conducted for South Carolina DOT, which found that 60% (19 out of 32) of responding state DOTs did not include the road user costs in life cycle cost analysis [22].

The TDOT does not calculate the road user costs for all the projects. As such, to understand the DOT practices of determining if road user costs should be calculated and included on contracts, respondents were asked to select the criteria for such decision (Fig. 2). The duration, location, and complexity of the project were the top three factors in determining the inclusion of the road user costs. Although the dollar value of the project might appear to be the primary factor in such determination, it is not considered as important as the duration, location, and complexity of the project.

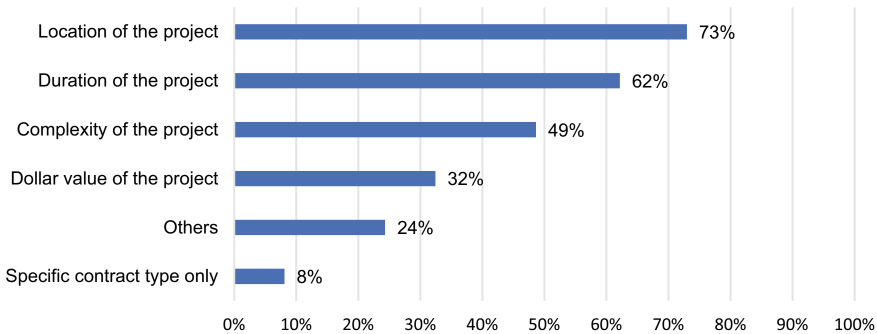

Fig. 2 Criteria to determine if road user cost should be calculated

State DOTs are more likely to calculate the road user costs for projects in urban areas with higher traffic volumes and projects that need to be completed in a short amount of time to minimize the impacts on road users.

5.2 Road User Costs Calculation Methodology

The road user costs calculation methodologies vary by state. Sixty-two percent of the respondents have their own state-specific methods (Fig. 3). However, part, or whole of the methodologies for most state DOTs is based on other standard methodologies. For example, the delay time in work zone is generally calculated using the methodology from the Highway Capacity Manual [27]. The delay time calculation presented in the FHWA methodology published in the *Work Zone Road User Costs: Concepts and Applications*, is also based on the Highway Capacity Manual [18].

Figure 4 compares the currently used and preferred tool types to compute road user costs in various state DOTs. The responses indicate that majority of state DOTs prefer and use spreadsheet-based tool. However, a spreadsheet-based tool is used by

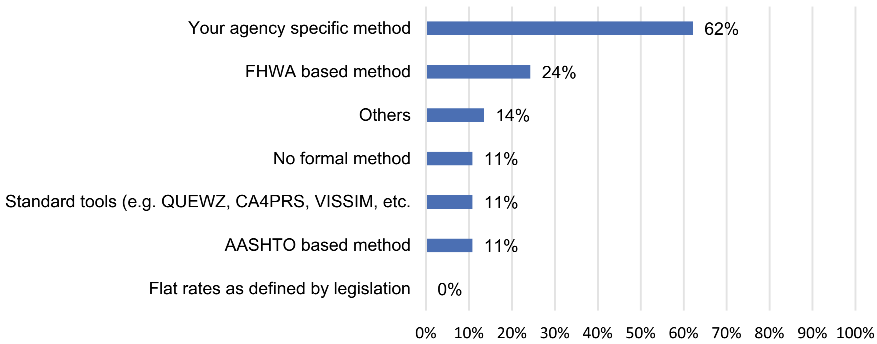

Fig. 3 Criteria to determine if road user cost should be calculated

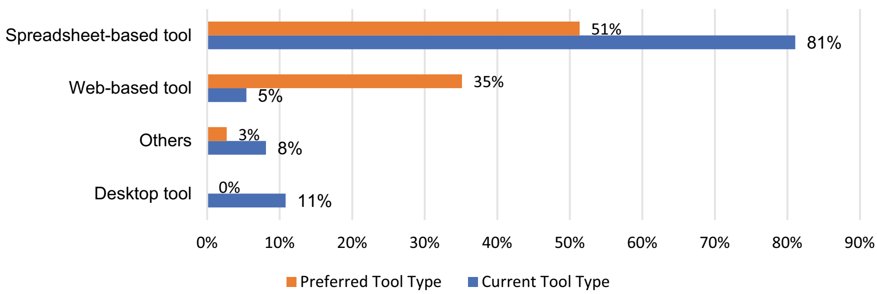

Fig. 4 Preferred and currently used road user cost calculation tools type

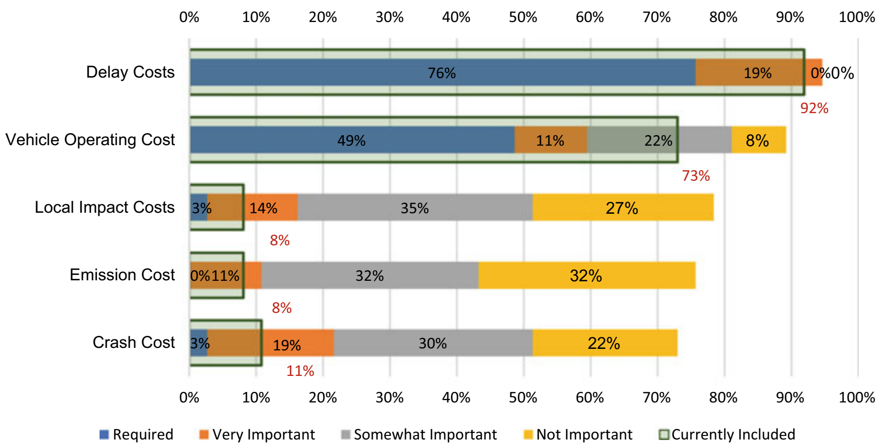

Fig. 5 Inclusion and importance of road user cost components

more respondents than preferred while web-based tool is used by less respondents than preferred. None of the respondents preferred desktop tool, probably because state DOTs are utilizing desktop-based tools developed a long-time ago. Such tools often tend to look outdated and cannot be accessed from multiple computers without installing on each computer. This trend towards web-based tools is also apparent in other construction tools used by state DOTs such as AASHTOWare Project [2] that has slowly migrated from being a desktop tool to a web-based tool over several years. AASHTOWare products are widely used by state DOTs for various purposes including daily work report data collection from construction sites [23].

The road user cost consists of five major components: (a) delay cost, (b) vehicle operating cost, (c) emission cost, (d) crash cost, and (e) local impact costs (Fig. 5). Most respondents indicated that the delay cost and vehicle operating costs are currently included in their road user cost calculation methodology. These two components are also considered essential by more than half of the respondents. While other road user costs such as local impacts, emission costs, and crash costs are considered somewhat important by many respondents, less than a quarter of respondents included such components in their road user calculation methodologies. This is most likely because of the lack of well-established methodologies and/or required data to quantify such costs.

The survey found that none of the state DOTs included all five components of the road user costs in their methodologies. The Florida DOT is the only state DOT that included four of the five components in its methodology. Seven state DOTs included three of the five components. Eleven DOT included two components. Similarly, six state DOTs included only one component. Finally, three states do not calculate road user costs for their construction projects.

6 Discussions

While existing road user calculation methodologies might have been serving well for state DOTs, several improvements can be made. First, different values of hourly time value of money can be considered for various locations in the state. This ensures that both the construction costs as represented by the bid amounts and the road user costs account for the regional economic conditions while evaluating the bids. Second, a consistent methodology and easy to use tool should be developed to ease the use of the road user costs in more projects and reduce subjective biases. Third, the rates such as value of time and fuel costs should be updated regularly to ensure that the values represent the current market conditions.

7 Conclusion

Many state DOTs have developed their state-specific methodologies to compute road user costs for various purposes including incentives/disincentives determination, A + B contract evaluation, and lane rental cost determination. Some state DOTs lack any systematic road user costs calculation methodologies while others had varied methodologies within the same state DOT. Even if the road user calculation methodology is developed for a state DOT, the road user costs are not calculated for all projects. The decision on whether to calculate the road user costs primarily depends on the duration and location of the projects. Most state DOTs prefer a spreadsheet-based or web-based tool to automate the road user cost calculation. The delay cost and vehicle operating costs are two most widely used components of the road user costs.

The findings of the study represent the most comprehensive comparison of the current practices of calculating and utilizing the road user costs in various state DOTs in the U.S. The findings are expected to aid state DOTs in developing a new road user cost calculation methodology or improving the existing one.

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Mass Timber: A Review of Typologies and Environmental Benefits

A. Gray and A. Sadoughi

1 Introduction

With growing interest in prefabrication, modularity, and environmentally friendly design, mass timber buildings are gaining in popularity around the world, proving that wood can replace traditional materials like concrete and steel as the primary structural material even in tall buildings. Mass timber, also known as engineered wood, is a category of building materials that incorporates multiple pieces of wood together to form large structural pieces, often beams and panels. Whereas solid-sawn timber requires large trees, which take a long time to grow, engineered wood can use younger, smaller-sized trees, lower-quality lumber, various species, and even waste pieces. These pieces, often from species such as spruce, fir, pine, douglas fir, or larch, are conjoined into large, consistent pieces that can provide reliable structure even in tall buildings [17: 13–14]. They allow not only a faster and more simplified design and assembly process, but limit construction noise, reduce environmental impact, and provide a high level of aesthetic quality.

Glue-laminated timber, or glulam, was one of the first engineered wood products to be developed, originating in Switzerland in 1909 [17: 14]. Glulam includes highly structural, stress-rated wood products, most notably beams. Consisting of thin planks of wood, or lamellas, which are finger jointed and glued together in parallel, glulam not only has a higher strength to weight ratio than steel but is stronger and stiffer than traditional lumber [2: 4, 12]. Because it incorporates many smaller pieces, it does not rely on tree size and can be made into massive beams, bridging far longer spans than single pieces of traditional lumber.

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Cross-laminated timber, or CLT, came along much later in the 1980s, also in Europe, and has since become a major player in the construction industry. Consisting of large panels of finger jointed lamellae, each layer of CLT is oriented perpendicular to the previous layer. These panels are generally glued up with odd numbers of layers in large presses [17: 15–17]. With a high level of strength and rigidity in both directions, these panels have been revolutionary in building, competing with concrete and steel as appropriate materials for large structures. As they are generally precut at the mill, details such as the overall dimensions, edge profiles, and windows and doors can be machined before ever reaching the worksite, vastly simplifying the assembly process and reducing time and waste [1]. CLT can also be manufactured with lower grade woods as well as offcuts, making it significantly more efficient than standard lumber in material usage [11: 3].

While glulam and CLT are currently the most notable and most popular mass timber products, there are certainly others, each with a purpose and a place. Laminated veneer lumber (LVL) includes much thinner layers of wood (often 3–4 mm). Laminated strand lumber (LSL) consists of flakes of wood glued together and is stronger than CLT. Parallel strand lumber uses thin strips of wood glued into large pieces [17: 14–15]. Nail-laminated timber (NLT) is less expensive than CLT [8]. Dowel-laminated timber (DLT) uses dowels rather than glue or nails and can be completely natural and nontoxic [17: 124].

The environmental advantages of mass timber are substantial, which merits a shift from traditional materials like concrete and steel towards timber in the structure of large buildings. Compared to concrete and steel, mass timber offers far lower embodied carbon and energy, reducing its global warming potential. Under proper forest management, it is completely renewable and can also be reused with ease. These advantages, however, are not universally applicable to mass timber. It is essential to source timber from local and sustainably managed forests to minimize transportation as well as ensure that timber is harvested appropriately and without over-exploiting forests.

2 Structural Components and General Uses

The two main categories of mass timber structural types are panels and beams. Mass timber buildings can include panels, beams, or both products depending on construction types and design requirements.

2.1 Mass Timber Panels

Mass timber panels can satisfy many functions, from walls to floors to roofs and beyond. CLT is currently the most popular choice for mass timber panels, but similar trends apply to other panel materials, particularly dowel-laminated timber, which is revisited in Sect. 6. Manufacturers produce panels of varying thicknesses, widths, lengths, and number of layers, which provide a good selection for satisfying structural necessities.

Wall panels can provide a high level of both lateral and vertical structure. Load-bearing walls usually use panels of at least 5 layers, whereas partition walls often use thinner 3-layer panels. Panels are usually between 2 and 7 inches thick depending on structural requirements [3: 2]. Shear walls are large, thick walls that span a significant portion of a building and offer high lateral support. Often used in elevator shafts and building cores, shear wall panels transfer large loads, such as wind loads, to the building's foundation [23: 14].

Floors typically use thicker panels of at least 5 layers and at least 6 inches, although thickness is quite dependent on structural requirements [3: 2]. Roofs can use a variety of panel dimensions, which are often reminiscent of floor panel dimensions [17: 107, 111–112, 204].

Glue-laminated timber can also be made into panels, although they are not as wide as CLT panels. GLT panels are often used as a roof or floor decking, but can also be used as walls, including load-bearing walls [25].

2.2 Beams

GLT is currently the most popular choice for mass timber beams. Still, materials like nail-laminated timber or dowel-laminated timber are used similarly [17: 293–294] and have their advantages, like lower cost, reduced environmental impact, and quicker manufacture. In addition to straight beams, curved beams are possible as well, allowing more organic shapes and higher creativity in building design. Glulam beams come in a few different appearance grades, including framing, industrial, architectural, and premium. Additional strength grades are categorized by manufacturers [2: 5]. With proper adhesives and treatment, glulam beams can even be used in exposed applications [2: 8].

Straight beams come in both stock and custom sizing, with stock widths generally ranging from 3 1/8″ to 6 3/4″ [2: 5]. Common uses include columns/posts, beams, purlins, rafters, roof ridges, floor joists, and garage door headers [2: 13–16]. I-joist compatible beams, which come in similar sizes to conventional I-joist sizes, offer a direct replacement to I-joists [2: 12]. Special variations of layer thicknesses are common, allowing optimization for specific purposes. Some hybrid beams of glulam with LVL outer layers even exist [2: 7].

Curved beams are generally made specifically for custom applications and many manufacturers offer curved beam capabilities. Often used in roofs, curved beams allow highly unique structures. Other glulam roof pieces, such as ribs and trusses, are also common and come in a wide variety of sizes with a large offering of custom sizes.

2.3 Additional Mass Timber Products

Mass timber can be used alongside concrete in timber-concrete pieces, in which mass timber panels or beams are topped with a layer of concrete to create a completely precast composite panel [22: 17]. Another notable mass timber product is the CLT access mat. Access mats are used to create temporary roads for construction vehicles and the use of CLT allows up to 2/3 less weight than traditional hardwood mats while providing greater strength [26]. Access mats can also be built into shoring boxes [24].

3 Structural Framing Systems

Between strong, load-bearing panels and beams, there are a few ways to erect a mass timber structure. Mass timber buildings fall into three main categories: platform construction, balloon construction, and post and beam construction [8, 13: 186]. Mass timber panels are highly structural and replace concrete and steel even in large buildings. These panels, often CLT, replace traditional stud walls, offering greater simplicity and strength [13: 186]. Many buildings are constructed without beams, using panels alone for structure, either in platform or balloon construction. In both platform and balloon construction, a honeycomb design is often utilized, which uses a decentralized structure of load-bearing interior and exterior walls to support the weight of the building [17: 50]. In platform construction, floors are built directly on top of walls. In balloon construction, which is far less common in North America, multiple stories of wall structure are built at once and floors hang off of walls using hangers or ledgers.

CLT panels alone can support buildings of up to 10 stories, but taller structures generally require a glulam mega-frame [8]. This style of construction is referred to as post and beam construction and consists of a structural frame of beams, often glulam or LVL. To finish the structure, mass timber panels are often used, such as for floors, walls, and roofs [17: 265–269].

4 Assembly

This section includes common practices in assembly, including exterior and interior walls, finishing panel floors, and hybrid materials and construction.

4.1 Exterior Walls

Exterior walls pose specific challenges due to their interface with the elements, which requires certain special attention. Water and moisture management is essential in prolonging the life of mass timber elements as well as preventing any loss in strength. Deflection, drainage, drying, and durable materials are four key focuses of designing the exterior of a mass timber structure. First, water should be deflected away from the building to limit penetration. Second, water should easily and quickly drain away from the building, limiting the time it has to penetrate any wood elements. Third, any elements that do get wet should be able to dry quickly, which can be done by incorporating a cavity for ventilation between the exterior cladding and exterior wood elements. Lastly, wood should be durable and have moisture prevention when needed [13: 411–414]. Many products exist to create moisture barriers, from liquids that can be applied with a brush or sprayed on to membranes that are installed over mass timber pieces. Various designs exist, including some that are breathable, enhancing drying ability without compromising moisture protection [20: 98–104].

A design example of a well-insulated exterior wall includes a vapor-permeable moisture barrier installed over exterior CLT panels. Rigid insulation, such as extruded polystyrene, expanded polystyrene, polyisocyanurate, or rigid mineral wool, is applied on the outside of CLT panels. Furring strips are applied vertically over the insulation and screwed through into the CLT with long screws. The spacing between furring strips allows drainage and ventilation but could be filled with thinner pieces of rigid insulation if the design permitted. Exterior cladding is attached to the furring strips [13: 422–425]. Various other designs exist, meeting different requirements for different climates and applications. Many designs are similar to those used in traditional wood construction.

The corners of exterior walls deserve special attention. Airtightness is essential, requiring sealing of the joint with a sealing tape [23: 82–83].

Windows and doors should also receive special attention to prevent water ingress and damage. The exterior plane of a window frame should be installed in the same plane as the CLT panel's water retention barrier. The same themes of deflection, drainage, drying, and durable materials are also key in window and door installation. Water should be deflected away as well as possible, especially by the window sill [13: 427–428].

The interior side of exterior walls can be treated insulated and finished similarly to interior walls.

4.2 Interior Walls

Mass timber structures often involve a decentralized, honeycomb structure where interior walls can be load-bearing elements. Walls that are not load-bearing are referred to as partition walls. For both types, walls can either consist of single panels or pairs of two thinner panels with insulation between them [17: 105–108]. Gypsum boards can be installed outside wall panels both as insulation and to provide a more finished design [23: 56]. At times, when treated properly, CLT walls are left exposed, especially in non-residential buildings, as an aesthetic touch.

4.3 Finishing Panel Floors

Floor panels are generally not left bare. Traditional flooring methods are generally applicable to mass timber buildings, including over CLT floor panels. One common method involves a cement screed, which various types of flooring can be installed over. First, a layer of granular material such as small stones covers the floor, which is then blanketed in a layer of sound insulation. A thin layer of concrete is poured on top and leveled, creating a surface for the flooring. A dry screed can also be installed, which avoids introducing moisture to the floor panel but does not perform as well in vibration attenuation [23: 63–65].

Similarly, ceilings are often insulated to prevent noise and vibration travel. Most commonly, gypsum boards are suspended from the panels, and decoupled mounts such as springs strips or whip arms are often used [23: 65–67].

4.4 Hybrid Materials and Construction

While many buildings have entirely mass timber structures, the hybrid use of traditional materials and mass timber in a single building's structure is common, especially in taller buildings. Steel and concrete are still occasionally used to offer additional support in taller structures. Some buildings use interior steel frames, which can take a load off of the load-bearing interior walls, allowing larger, more open interior spaces [17: 61]. While concrete foundations are still typical in mass timber buildings, some designers choose to build lower stories out of concrete as well for extra stability [17: 142, 245, 321, 327]. Concrete cores are also used to add structure and can be used as elevator shafts [17: 153].

Another instance of hybrid construction is the use of traditional light wood framing with mass timber. Light wood frames can be cheaper than CLT and are occasionally used in mass timber structures for partition walls [17: 115–117].

An interesting integration of concrete into mass timber structures is the attachment of concrete slabs onto the bottoms of CLT floor panels. This has been done to increase thermal mass and energy efficiency [17: 85–87].

4.5 Bridges

Mass timber, and glulam, in particular, have opened up many possibilities for the use of mass timber in bridges. The strength, as well as the size of glulam beams, allows them to span great distances, making them a perfect material for bridges. They eliminate weight, contribute towards sustainability, and enhance aesthetic quality as well. With proper design, treatment, and moisture prevention, mass timber bridges can last at least 75 years [7].

5 Environmental Impact and Sustainability

The global construction industry uses more resources than any other single industry [9: 1] and is responsible for over a third of global carbon emissions [19: 3]. The production of concrete alone accounts for ~8% of total anthropogenic carbon emissions [16]. Apart from the amount of carbon emissions, which constitute global warming potential, concrete is not a renewable material. Despite the ability to incorporate some recycled content, concrete relies on non-renewable materials that can eventually run out [6: 2]. Steel, while recyclable, requires high levels of energy to process. In fostering more sustainable and environmentally responsible development, which is imperative in securing a healthy future for mankind and for the Earth, sustainable and environmentally responsible materials are essential. Mass timber has the power spark a trend of sustainability in construction material choice, reducing the impact the construction industry has on the environment and the climate in a major way. Despite its relative infancy and the associated disadvantages, such as greater transportation distances than traditional materials, mass timber overwhelmingly performs better than concrete and steel in its associated global warming potential. There is significant room for improvement, and as the industry matures, its environmental impact will diminish and it will settle into place as a primary sustainable building material.

Mass timber has shown great promise in reducing buildings' global warming potentials (GWP). Within the initial Cradle to Gate boundary of material production through construction phases, mass timber's smaller environmental impact is already evident. Mass timber's reduction in greenhouse gases also increases with time. Because the wood sequesters carbon, mass timber structures keep carbon out of the atmosphere and prevent it from adversely affecting the climate. When forests are sustainably managed and replanted at a similar or greater rate to their rate of harvest, as many forests in the United States and Canada are, the net effect is a reduction in atmospheric carbon. In a study on CLT buildings in Japan, it was found that the effects of carbon sequestration surpass the effects of CLT production around 30 years into the life of mass timber products, passing the point of carbon neutrality to become a net carbon sink [18: 1].

While global warming potential is already almost universally lower for mass timber buildings when compared to concrete and steel alternatives, energy use trends are less uniform. While most studies demonstrate a reduced energy demand for mass timber structures, both overall and in various stages of a building's life, reduced energy use is not a given with mass timber construction. It is important to note that the energy demands are factored into the overall global warming potential. Thus, even if the energy demands are higher in certain mass timber structures, the global warming potentials of mass timber structures are still generally much lower than their concrete or steel counterparts.

A building's operational energy is of great importance because it lasts the duration of a building's life and falls upon the building's residents. Heating and cooling energy are the main sources of variance between building materials, as mass timber and concrete have different thermal properties. Mass timber's low thermal conductivity and air-tight connections contribute to its good insulative properties, reducing the need for high energy levels for temperature regulation [12: 2]. A recent study in China found that mass timber can offer up to four times more energy savings in colder regions where heating is used more than cooling, suggesting that mass timber is especially well equipped to provide reduced energy usage in cooler climates [10].

While mass timber construction is generally a major step towards sustainability, there are many variables that effect its full impact. First, a sustainable timber source is imperative. Forests managed properly with rotational harvesting rather than clear-cutting produce less, but they promise a dependable and sustainable supply of timber for generations to come [19: 8]. Sustainable timber harvest is virtually carbon neutral because of the carbon sequestered in the wood used [4: 7]. In the case of mass timber, structures have the potential to become carbon negative over time because of the carbon sequestered in the wood as well as the new growth capturing additional carbon in the forest. Organizations such as the Forest Stewardship Council (FSC), the Sustainable Forestry Initiative (SFI), and the American Tree Farm System (ATFS) all offer certifications for sustainably sourced forest products. These certifications ensure that products are not contributing towards deforestation or other major harm to forests. As mass timber expands, it is important to ensure it is sourced responsibly as to not create a negative impact, especially through deforestation [14: 6].

Another important consideration is the transportation distances, which contribute significantly towards the overall global warming contribution, smog potential, acidification, eutrophication, and ozone depletion [5: 9]. A study by Liang et al. demonstrated that, at times, transportation can account for over 20% of total carbon emission in the mass timber construction process (from timber procurement to end of life) [15: 10]. Transportation distances for mass timber components were often more than ten times greater than those of concrete components [15: 5]. Mass timber is still in its infancy and will likely undergo a diminished environmental impact with age. The contribution towards global warming potential along with other effects is expected to decrease over time as more mass timber suppliers join the market, making it easier to source locally. While mass timber is an improvement over traditional materials in ecological footprint, it is not necessarily an appropriate material for all regions. In regions where forests are plentiful and the timber industry has a presence, it makes sense to build with timber. In locations such as deserts or plains, especially those that are far from forests, it might not be as sensible to prioritize mass timber because of the absence of timber as a local resource and the associated transportation emissions. While it still might be an improvement over concrete and steel, it is quite possible that mass timber is not the ideal building material for these regions.

In considering a massive shift towards mass timber, the question arises as to the sustainability of timber supply. Can we make this shift without depleting our forests? The United States peaked in lumber demand in 2005 and, according to Karacabeyli and Douglas [13], even if all new multi-residential and non-residential buildings were built from CLT, demand would not reach the levels seen in 2005 (457–458). Furthermore, they note that forests in the United States and Canada see relatively good forest management, suggesting that even if mass timber demand reached an exceptionally high level, sustainable forest management practices would not permit overharvesting [13: 457].

6 Future Directions

Mass timber is a relatively new phenomenon and is constantly being researched, improved, and augmented. While many promising ideas are still being tested and perfected, others show promise but have yet to receive much attention. A few exciting future directions are evaluated here.

CLT and GLT are two renewable building products and are quite revolutionary in enhancing sustainability in large buildings. One remaining environmental concern is the adhesives used, which are both toxic and prevent disassembly at the end of life. Without the use of adhesives, a cheaper, faster, and more environmentally friendly mass timber panel could be made that performs similarly to CLT itself [21]. Two materials currently aim to solve this dilemma: interlocking CLT and dowel-laminated timber.

6.1 Interlocking CLT

Interlocking CLT (iCLT) involved precision machined dovetail profiles that lock together, forming a completely mechanical bond between lamellas. Smith's research has shown that iCLT can outperform CLT in lateral load resistance [21].

6.2 Dowel-Laminated Timber

Much like iCLT, dowel-laminated timber (DLT) however, is already on the market and has been used extensively [22: 5–6]. Because it can be made into either beams or panels, DLT is an exceptionally exciting material that has the potential to replace both CLT and glulam as the primary mass timber material, providing similar structural qualities, but at a lower cost, requiring less time, and creating a less harmful impact on the environment.

6.3 Reuse and Recycling

One of the promising aspects of mass timber, especially compared to conventional timber or concrete and steel, is its reusability. Panels and beams can be disassembled and repurposed at the end of life of the building, making them an exceptionally sustainable material choice. While it will likely be decades before large amounts of mass timber buildings reach their ends of life, devising plans for disassembling and reusing mass timber components is worthwhile. This is not only an environmental decision but an economic one as well.

7 Conclusion

Mass timber is a revolutionary building material, promising safer, quieter, quicker, and less wasteful construction with a great reduction in environmental footprint. In addition to all these dramatic improvements over traditional methods and materials, mass timber is still in its infancy. As its popularity grows and the industry matures, its efficiency is expected to soar as its environmental impact dwindles. With a negative carbon footprint, it can even have a positive environmental impact, posing a potential tactic for the mitigation of climate change. It is truly the building material of the future, paving the way for a brighter and healthier tomorrow.

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Building Energy Retrofits: A Review of Decision-Making Models

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1 Introduction

The increasing worldwide energy consumption and the environmental concerns, such as energy resource depletion, global warming, climate change, carbon emissions, acid rain, and waste accumulation, have attracted increasing attention in the past few years [4]. It has been estimated that the global energy needs will increase 28% by 2040 to reach 736 quadrillions Btu (British thermal units) [21]. In this respect, buildings are one of the most energy-intensive sectors, accounting for around 32% of global final energy demand, hence, playing a significant role in addressing energy issues worldwide [5]. In the United States, buildings accounted for 39% of total energy and 72% and electricity consumption [19]. Consequently, demand response programs and optimization techniques are implemented in the residential sector as a practical solution for reducing electricity consumption in residential buildings [35, 36]. Furthermore, in the construction industry, the term "green buildings" was introduced as part of the sustainable development efforts in the industry to mitigate the buildings' detrimental environmental, economic, and social effects [23]. One of the sustainable development efforts is the demand for energy-efficient and low-carbon buildings. These high-performance buildings can reduce energy use and lifecycle costs while maintaining the indoor environment's quality [34]. However, the cost of using these strategies seems to be a significant obstacle to implementing energy efficiency measures (EEMs). A viable solution needs to strike a reasonable balance between costs and environmental benefits [2]. This need for optimizing energy performance through rational consumption, which takes economic consideration into account simultaneously, has led to the introduction of a concept entitled *"Energy Retrofit."*

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An energy retrofit, the most feasible and cost-effective method of reducing the energy demands of existing buildings, is defined as any operational and physical change in the building's characteristics along with its equipment or user behaviors to improve buildings efficiency [43].

A wide variety of energy retrofit measures can improve building energy efficiency. Different classifications have been proposed across many studies pertinent to building specifications and retrofitting projects. In one of the most comprehensive analyses, Jafari and Valentin [19] categorized energy retrofitting measures into five main groups:

- *Controlling measures*: implementing appropriate controls and monitors for the mechanical and ventilation systems, lighting, as well as providing the efficient use of multi-functional equipment.
- *Load reduction measures*: enhancing the mechanical systems, appliances and lighting conditions by replacing them with more energy-efficient models.
- *Enveloping measures*: applying additional insulate and air-seal layer in the roof or ceiling, walls, and floor; replace the windows and doors with energy-efficient ones.
- *Renewable energy technologies*: providing renewable energy sources such as solar thermal systems, solar photovoltaic/thermal systems, geothermal power systems, etc.
- *Human behavior*: changing energy consumption patterns of occupants [19].

By developing various energy retrofit measures during the optimization of buildings' energy, decision-makers can choose the most appropriate practices based on their needs and expectations. The wide range of involved parameters makes the decision-making process far more complicated. Decision-makers should consider different economic, environmental, and energy-related parameters, such as indoor comfort, legal regulation, as well as technical and social factors, to create the best possible balance across end-user requirements [3]. Yet, it is quite noticeable that financial parameters are often prioritized in most decisions over environmental and social considerations [20].

To overcome this challenge and to address the multi-objective optimization problems, numerous decision aid approaches have been proposed in the past few years, each of them focusing on different aspects of decision-making in energy retrofits. They enumerated numerous variables and objectives, such as total costs or energy conservation, among many others. A thorough interaction among all the involved factors needs to be considered to calculate an optimal solution. In addition, the probable uncertainties in these retrofit problems, such as occupant behavior, climate changes, variation in energy costs, and governmental policy changes, can also easily affect the success of a specific decision [14]. Decision Support Systems (DSSs) can help decision-makers more thoroughly consider elements included in a given analysis to choose the optimal solution or avoid unfavorable scenarios [22].

This study presents the preliminary result of a literature review on the decision-making analyses in energy, DSS models for building energy retrofits, and their practicality to choose the best strategy. The study provides recommendations for potential applications of DSS in the decision-making processes of energy retrofit projects.

2 Literature Review

2.1 A Building Retrofit

"Energy Retrofit" is considered the most feasible and cost-effective way to improve energy efficiency in existing buildings [43]. As Kontokosta [24] defined, an existing building's retrofitting process originally appeared as a critical strategy of reducing energy consumption and carbon emission. With the replacement rate of existing buildings by new averaging 1.0–3.0% per year, retrofitting the existing buildings has a much greater capacity to reduce energy consumption in the building sector [38]. This essential technique can lead to the accelerated transformation of the construction industry to a sector with low-energy demands.

Energy Efficiency Measures (EEMs) are employed within a building retrofitting project to improve total energy performance. These measures minimize the energy need of buildings by reducing the consumption of existing systems through upgrades or refined controls, along with promoting renewable energy resources [33]. Figure 1 presents a sample of energy retrofit techniques or measures classified into four major groups: *Energy Demand Reduction, Energy Efficient Equipment, Energy Production Systems, and Energy Consumption Patterns.*

When implementing these measures, the decision-makers should make sure occupants' requirements are met. Therefore, the optimal retrofit solution is a trade-off between energy and non-energy-related factors [27]. In other words, an energy retrofit project's success is based on the selection of energy efficiency measures capable of satisfying stakeholders' diverse requirements [33]. Considering the fact that retrofitting of existing buildings would be capable of offering remarkable opportunities to reduce global energy consumption, many governments and international organizations have emphasized building retrofitting projects. In this regard, numerous policy guidance, financial assistance, and technical supports have been provided by each country to assist the implementation of EEMs in existing buildings and the construction of new ones [47]. For instance, the United States federal government provides significant financial assistance to support existing building retrofits projects.

The key point in the definition of energy retrofit is that by applying energy retrofits, user indoor comfort and satisfaction should remain acceptable or improve. Retrofitting projects are not only seeking energy consumption reduction. Instead, they try to improve the building's serviceability and provide end-users with acceptable indoor thermal comfort under a given set of operating constraints through upgrading the equipment, implementing optimization techniques, or introducing

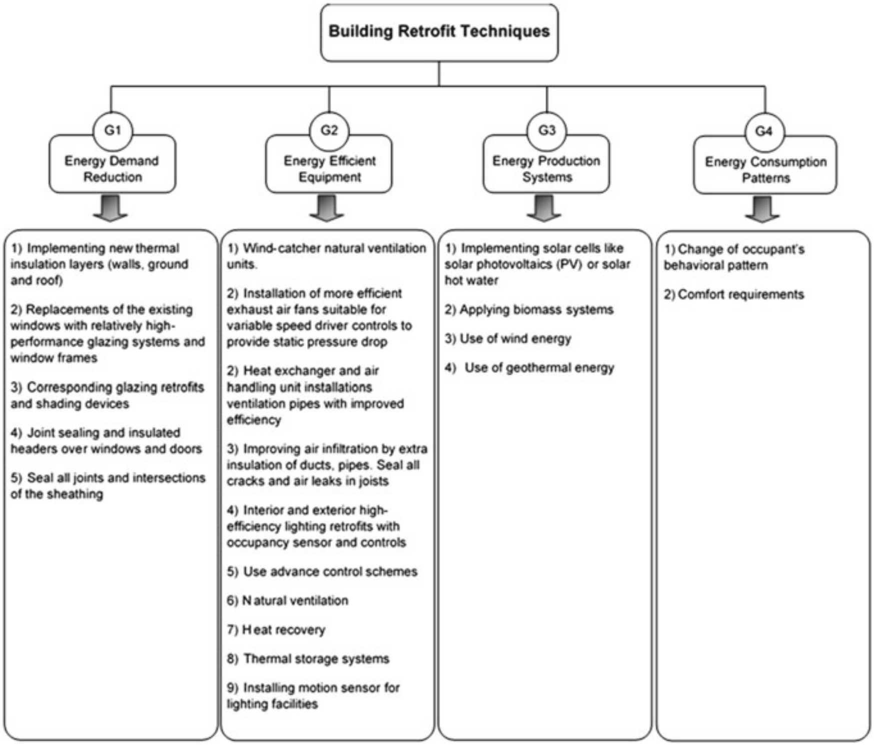

Fig. 1 Building retrofit techniques [27, 43, 44]

thermal storage facilities [35, 36]. The widespread application of intelligent buildings is another evidence in this regard [6].

2.2 *Decision on Energy Retrofit*

Although retrofitting existing buildings is assumed to be one of the most effective sustainability approaches in the built environment at relatively low cost and high uptake rates, identifying the most cost-effective measures for a specific project may still be a technical challenge due to the wide range of available retrofit options. Noris et al. [32] argued that in choosing a retrofit scenario for a specific building, engineering judgment, cost–benefit analysis, and energy simulation have been employed but rarely do we consider the potential effects on indoor environmental quality (IEQ) for this selection. Thus, the retrofit measure's decision for a specific building can be considered a multi-objective optimization problem subject to many constraints and limitations. This includes but is not limited to building characteristics, financial limitations, project target, building services types and efficiency, building materials, etc. [27]. The selection's complexity may be far more evident when we realize that financial considerations are not the only criteria for selecting a retrofitting project. Several approaches have been developed in the past decade to deal with the challenging process of selecting energy retrofit measures. This includes cost–benefit analysis, multicriteria analysis, and multi-objective optimization [3]. What follows is the literature review of each category of analysis.

2.2.1 Cost–Benefit Approaches

Stakeholders' decision on investing in retrofit projects often depends on the returns on investment. In practice, a retrofit project often incorporates several retrofit alternatives for which conducting an economic assessment of the cost-effectiveness may be necessary to prioritize them [26]. Cost–benefit analysis provides the decision-makers with the opportunity to investigate the expected benefits achieved from a retrofit project. As a result, the viability of a retrofit investment can be determined by considering whether the gains can surpass the involved cost. In this regard, the assessment of retrofit alternatives can be carried out from three aspects of sustainability: environmental [11], economic [10, 12], and social [28]. Numerous studies have been performed in the past few years to carry out the economic assessment of retrofitting the existing buildings to assess the costs of adopting retrofit measures [1], while environmental and social aspects have been less considered. These costs can be categorized in a systematic manner as depicted in Fig. 2.

Several factors affect the cost of retrofit projects, such as the characteristics of the building stock, legislative and regulatory requirements, and applied retrofit technologies. On the other hand, the benefits are influenced by factors such as the climate characteristics and building occupants' behaviors [26]. In General, retrofit projects provide their owners with benefits, including:

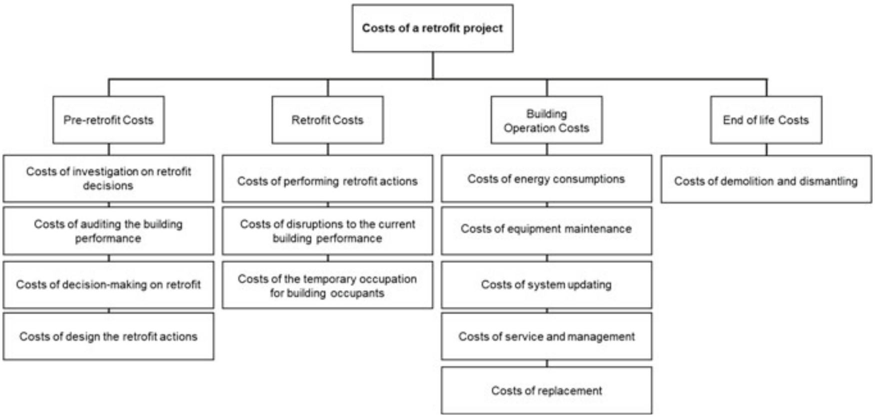

Fig. 2 Various costs of a retrofit project

- **Economic benefits**: reducing the maintenance and operating costs, offering tax-saving incentives by the governments, reducing exposure to energy price volatility [27], extending the building life expectancy [40], enhancing property value and rental level of existing buildings [26], and higher tenant retention [24].
- **Environmental benefits**: reducing the energy consumption, CO_2 emissions, and mitigating global climate change objectives [42], improving the energy security, minimizing the embodied energy for buildings [31].
- **Social benefits**: improving the thermal comfort of occupants and indoor air quality [32], promoting user productivity, and introducing new job opportunities to the society [20].

Although studies have indicated that the main reason for implementing an energy retrofit is to reduce the operational energy requirements, economic benefits are of paramount importance to encourage owners to apply these measures. As Tokede et al. [40] asserted, among all these benefits, cost and energy are arguably the predominant drivers of retrofitting, however, financial justification is not an easy task. It should be noted that since 2000, energy is the most convincing basis. However, environmental and social considerations are becoming far more influential in recent years [30].

Having examined the costs and achieved benefits of retrofit scenarios by using economic evaluation methods such as Net Present Value (NPV) and Internal Rate of Return (IRR), decision-makers would be capable of assessing the cost-effectiveness of retrofit investments. In addition to NPV and IRR, a variety of economic analysis methods, such as overall rate of return (ORR), benefit–cost ratio (BCR), discounted payback period (DPP), simple payback period (SPP), and Life Cycle Assessment (LCA) have also been used to evaluate retrofitting investments. Among all these economic approaches, the SPP, NPV, and LCA are the most predominant methods [43].

Several studies have been carried out to perform the cost–benefit analysis of retrofit projects. Each of them adopted different analytical methods for this purpose. A summary of some of these studies can be found in Table 1. During the evaluation process of different alternatives, considering solely the initial costs of an option would not guarantee the most cost-effective solutions. Hence, to analyze a building retrofit's overall cost-effectiveness during its lifecycle, lifecycle cost analysis (LCCA) should be applied. This technique, which is commonly regarded as a powerful method to quantify the potential environmental impact of a product or a service, has gained a growing application for building retrofitting. In the LCCA method, the total cost throughout the building life, including planning, design, implementing, support, maintenance, replacement costs, and any other costs directly attributable to owning or using the alternatives, is holistically assessed. The lifecycle cost is associated with estimating future cash flow to evaluate each alternative's overall cost and resulting energy savings [43].

Regardless of the LCCA method's ability to analyze economic aspects of buildings during their life span in a comprehensive way, there are still several methodological challenges that result from the uncertainties involved in defining lifecycle scenarios or the analytical variables used. One of the significant existing deficiencies arises from

Table 1 Previous cost–benefit studies in energy retrofit decision-making

References	Objective functions	Tools and techniques	Description (cons and pros)
Sağlam et al. [37]	– Minimizing primary energy consumption – Minimizing global cost (based on NPV)	EnergyPlus Net present value Sensitivity analyses	– Integrated the effect of occupant behavior into the energy and economic assessment of building retrofits – Considered several cost elements (investment, replacement, energy, maintenance, and residual value) – Applied simulation is simple
Beccali et al. [8]	– Minimizing primary energy consumption and embodied energy – Minimizing energy and emission payback time	– Life cycle cost (LCC) – TRNSYS	– Considered all phases of the building lifecycle from the production of the material to the demolition – Applied simulation is simple – Considered embodied energy – Limited retrofit interventions were considered – No uncertainty is considered
Kumbaroğlu and Madlener [25]	– Maximizing NPV	– Life Cycle Cost (LCC) – Monte Carlo simulation	– Applied simulation is complex and timely – Limited variables were considered – The energy price uncertainty was addressed
Chidiac et al. [13]	– Minimizing Payback Period	– EnergyPlus – Regression analysis – Present value analysis	– Applied simulation is complex and timely – No uncertainty is considered – Limited cost elements (only installation and material costs) – Defining building archetypes assist evaluation of different buildings – Capable of ranking ERMs

(continued)

Table 1 (continued)

References	Objective functions	Tools and techniques	Description (cons and pros)
Bleyl et al. [9]	– Energy cost saving through the reduction of fossil fuel consumption	Dynamic life cycle cost and benefit analysis (LCCBA) to model cash flow	– Utilization of deep energy retrofit practice – Lifecycle analysis

experts' inability to anticipate all changes during a building's lifetime. Moreover, future decisions', such as changing tenants, may not be appropriately considered in many lifecycle models [40]. Several researchers expressed the need for more accurate uncertainty assessment methodologies to improve the reliability of results in the lifecycle appraisal. However, since a building is known as a complex context, its lifecycle is intricate with a diverse range of interdependencies [41]. To overcome these complexities, scenario modeling has been employed to shape lifecycle option appraisals. Having defined scenarios as descriptions of possible future conditions, the lifecycle assessment tries to reflect optimal and long-term performances in buildings. Although these scenarios are valuable approaches to portray a long-term view of events, predicting the future with 100% certainty seems inconceivable. Hence, the proposed frameworks could be illusory and unrealistic [40].

2.2.2 Multi-objective and Criteria Optimization Approaches

Various energy retrofit criteria have been proposed over the last decade, including the total cost, energy efficiency and energy savings, comfort factors such as indoor air quality (IAQ), thermal comfort, and the usable space for the occupants in the building. However, energy-saving and capital cost are the most commonly considered criteria for optimal construction retrofitting planning [3]. Due to these criteria' contradictory characteristics, the retrofitting project can be considered a multi-objective optimization problem with several constraints.

A multi-objective optimization method is an area of multiple criteria decision-making that contains more than one objective function to be optimized simultaneously. These objectives include, but are not limited to, economic, environmental, and energy-related, and occupant comfort objectives [18]. In this approach, a wide variety of criteria, including total energy consumption of the building, the annual carbon dioxide emissions, the initial investment cost, the NPV of retrofitting, occupant comfort, and indoor air quality, are often assessed, along with other potential criteria. Table 2 summarizes previous multi-objective optimization literature and their objective functions and a brief description of them.

It should be noted that many of the parameters used in the optimization models may not be known entirely, and the possibility of uncertainties is inherent and should always be considered. These uncertainties, such as the energy savings, the energy price, the discount and interest rates, and the interventions' failure rate, would significantly affect the accuracy of the model forecasts. Thus, in an accurate model, the sensitivity analysis seems necessary to check the uncertainties' influences [29]. As Fan and Xia [16] mentioned, *"A wide variety of available alternatives for retrofit as well as items to be retrofitted turn a problem into a high-dimensional optimization one. The situation gets worsened by the mixed-integer decision variables involved. The conflicting characteristics of objectives, like maximizing the building's energy savings and minimizing the payback period, would lead to an even more challenging optimization problem."*

Table 2 Previous multi-objective optimization studies in energy retrofit decision-making

References	Objective functions	Tools and techniques	Description (cons and pros)
Asadi et al. [3]	– Minimizing Retrofit Cost – Maximizing Energy Savings	– MATLAB – Tchebycheff programming – ISO 13790 – RC model (monthly)	– Considered several interventions – Electric lighting was not considered – Limited cost elements were considered – Considered only heating energy – Applied simulation is complex and timely – No uncertainty is considered
Diakaki et al. [15]	– Minimizing initial investment cost – Minimizing load coefficient	– LINGO software Compromise programming – Global criterion method and Goal programming	– The payoff matrix used to display each criterion independently – Applied simulation is quite simple – Considered limited variables (only window type and wall insulation) – Considered limited cost elements (only the acquisition of materials) – Only heating energy through thermal conductivity

(continued)

Table 2 (continued)

References	Objective functions	Tools and techniques	Description (cons and pros)
Fesanghary et al. [17]	– Minimizing the life Cycle cost (LCC) – Minimizing carbon dioxide equivalent (CO_2-eq) emissions	– EnergyPlus – Harmony search algorithm (HS) – Pareto front – LCA	– Considered the whole lifecycle emissions and all phases in LCA – Considered various design variables (only for building envelope) – Considered design new buildings instead of retrofitting – Applied algorithm is quite simple – No uncertainty is considered – Limited cost elements were considered
Wang et al. [43]	– Maximizing energy savings and economic benefits – Minimizing the payback period and environmental impacts	– Differential evolution algorithm – NPV-based economic analysis (LCC) – Sensitivity analyses	– Probable uncertainties like facilities failures were considered through sensitivity analyses – Applied simulation is complex and timely – No uncertainty is considered – Limited cost elements were considered – In energy savings calculations, only electricity was considered

(continued)

3 Discussion and Conclusion

A comprehensive building retrofit assessment seems necessary to promote a building's overall energy performance in a cost-effective manner; however, this evaluation will involve some difficulties in accurately forecasting and optimizing systems due to the complexity of facilities coupled with their environment. Recent studies

Table 2 (continued)

References	Objective functions	Tools and techniques	Description (cons and pros)
Wu et al. [46]	– Minimizing life Cycle Cost – Minimizing greenhouse gas (GHG) emissions	– Design Builder and EnergyPlus – Epsilon-constrained mixed integer linear program (MILP) – CPLEX – Pareto front	– Interactions between retrofit and building systems were considered – The lifecycle GHG approach includes embodied GHG emissions was applied – Several retrofit scenarios were considered for each building – Classified buildings within a category with similarities in critical characteristics saved time and computational effort – Applied simulation is complex and timely – No uncertainty is considered
Tan et al. [39]	– Minimizing CO_2 emissions – Maximizing cost savings – Maximizing energy savings	– Mixed Integer Programming algorithm	– Introducing a multi-period planning approach instead of a single-period approach – Offering energy-saving technologies as a service – Using complicated mathematical formulation – Limited variables were considered – No uncertainty is considered

have argued that about 80% of all EEMs are selected without evaluating other alternatives. In fact, rarely do stakeholders pick these measures based on systematic decision procedure, and more often than not, they rely on their fragmented expertise. Hence, the selection process is highly intuitive rather than logical. In order to avoid the highly intuitive selection of EEMs, a relatively large number of approaches have been proposed. As summarized in Tables 1 and 2, various models for the decision-making process of energy retrofit projects have been used. These approaches try to achieve the most optimal energy retrofit approach. It is important to note that due to the differences in building types, building structures, local environments, and energy-using groups, it is difficult to apply one energy retrofit on a global scale and to all the projects [7, 45].

In the cost–benefit approach, the main focus is on reducing the cost of building by reducing the energy cost. Most of the studies in this approach emphasize cost analysis through the buildings' whole lifecycle. Other analyses in this category include but are not limited to the payback period or net present value. This will ensure the accuracy of the analysis and provide more flexibility in implementing different energy retrofit measures. In addition, most of these approaches seem to be simple compared to the multi-objective and criteria optimization approaches.

The objective functions are not limited to only energy cost reduction in the multi-objective and criteria optimization approaches. Maximizing load coefficient, minimizing greenhouse emissions such as CO_2, and minimizing the environmental impacts are among the common objectives. In these approaches, it is also common to use the whole lifecycle analysis. Amid all approaches, the multi-objective optimization (MOO) method has gained a great deal of attention considering its ability to facilitate the selection process where a multitude of EEMs are available.

All things considered, the conclusion to be drawn is that the energy and environmental assessment of building retrofit measures is a complex evaluation. Energy consumption in the operation phase is affected by various factors, like climate, building characteristics, building occupancy, and use among mechanical equipment types and schedules. Hence, the quantification of the related energy savings can be attained by calculation of achieved energy savings through comparison of post-retrofit energy consumptions and the pre-retrofit ones. The LCA method allows the comparison of the operational energy consumption reduction and helps the decision-maker to figure out whether the resulted environmental benefits could be justified in a building lifecycle or might be overcome by other environmental burdens of the actions.

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Building Information Modeling in Canada: A Multidisciplinary Practical Analysis

H. Nasrazadani, K. Shahi, A. Shahi, and B. McCabe

1 Introduction

The Canadian construction industry represents about $120 billion in capital expenditure, approximately 7% of the Canadian Gross Domestic Product [32]. The industry employs over 1.3 million people, or 7.5% of the total workforce distributed across more than 120,000 enterprises [16]. As in many countries, the Canadian construction industry suffers from low productivity. To remedy, many developed countries worldwide have prioritised building information modelling (BIM) and related technologies. In many ways, Canada is lagging many of these other countries in adopting and implementing BIM [8].

BIM is a modern approach to represent an asset's physical and functional characteristics in a digital and interoperable format [7, 33]. It serves as a shared knowledge resource for information about a facility and forms a reliable basis for decisions during its lifecycle. BIM is a process of developing and managing a digital representation of a built asset whose physical and functional characteristics are a reliable basis for decision making [29]. Successful implementation of BIM has shown promising benefits, including better end products, enhancing productivity, providing a competitive advantage, and improving documentation. However, significant barriers against

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industry-wide adoption of BIM also exist, such as high initial investment costs, lack of skill/knowledge, lack of guideline, and lack of training [5, 6].

The use of BIM in design has been widely explored for generative design, energy modelling, and optimization [1, 21]. However, its applications in the construction and operation of facilities have not been fully implemented [13, 31, 36], despite tremendous potential [11, 12, 17, 24, 28]. Site superintendents and site coordinators seldom have the training to use BIM software, making it more onerous to communicate using BIM and exploit its potential to improve productivity.

Bringing BIM to the field can have benefits that outweigh its costs [22]. In contrast to 2D models, which often fail to demonstrate the project's volumetric aspects, 3D models give a more realistic presentation. Particularly, BIM allows mechanical, electrical, and plumbing (MEP) to be in the same model as structural and architectural elements. This feature has driven one of the BIM's most common uses on-site: clash detection [25]. It can also help the trades effectively identify inconsistencies and coordinate efficient construction plans for upcoming tasks. Another benefit of BIM is the seamless information exchange between parties on a centralized platform, facilitating collaboration across disciplines [15]. This collaborative platform allows stakeholders to engage in the evolution of the project over time. Lastly, the centralized format of BIM facilitates integrated documentation throughout the project's lifecycle [34]. Altogether, these benefits can lead to improved productivity, enhanced task efficiency, reduced rework, and saving time and budget.

Three BIM surveys were undertaken as collaborative efforts between academia and industry to capture the state of BIM implementation within the architecture, engineering, construction, and facility management industries (AEC/FM) in Canada. This paper presents some of those results and relates the findings to a case study in which the authors were involved.

Note that the surveys circulated primarily within the BIM community, and hence, the analysis does not represent the entire AEC/FM industries in Canada. Although significant efforts were made to advertise the survey throughout the industry, including promoting it at industry events, in Daily Commercial News, and targeted invitations to AEC firms, uptake by BIM non-users was minimal; therefore, the results must be considered from this viewpoint.

2 Survey Results

Figure 1 illustrates the distribution of the 872 respondents to all three surveys between 2018 and 2020. The majority of respondents were from the province of Ontario (76%), followed by Alberta (8%), British Columbia (6%), and Quebec (2%). The surveys also attracted 46 participants (5%) from outside Canada.

The respondents came from a broad range of disciplines within the Canadian AEC/FM industries. As shown in Fig. 2, 38% of participants are involved in architecture, including architects, architectural technologists, and interior designers. BIM

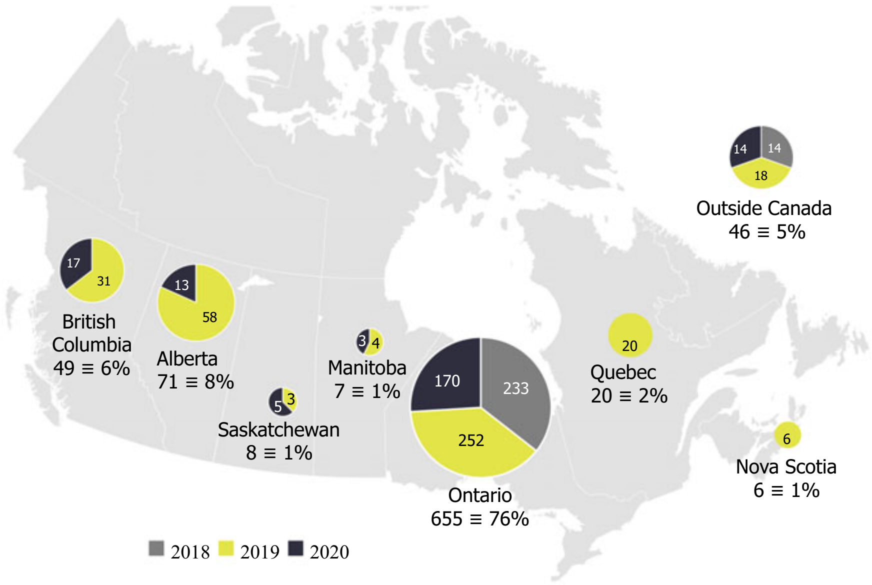

Fig. 1 Survey's reach throughout Canada

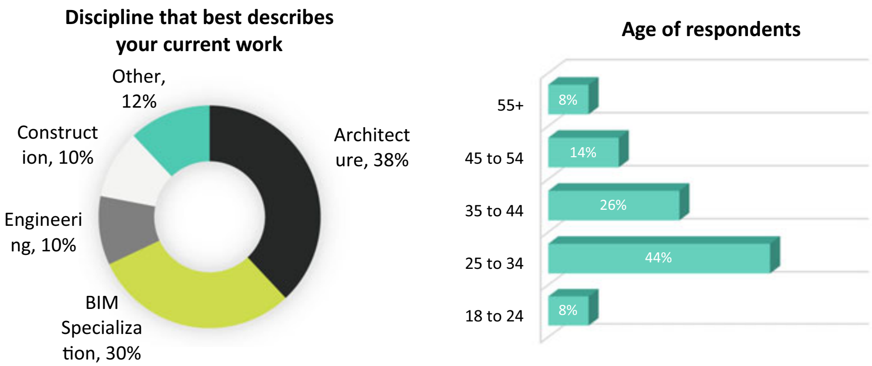

Fig. 2 Discipline and age of respondents

specialists comprised 30% of participants, representing BIM technicians, specialists, coordinators, managers, and virtual design and construction (VDC) coordinators and managers. Engineering disciplines included civil, structural, and mechanical; construction disciplines included project coordinators, managers, contractors, and estimators. The remaining 12% worked in education, software development, visualization, facility management, manufacturing, real estate, and law.

Other than the respondents' discipline, Fig. 2 represents age distribution, which was proportionate with each province's three-year national average. Notably, more than half of the participants were under 35. Although there was high participation of young professionals in the surveys, close to half (46%) had more than ten years of experience in their discipline.

The frequency of BIM projects was not proportional among disciplines, as shown in Fig. 3. Those in construction roles, such as project managers, construction coordinators, and contractors, had the highest non-BIM projects rate. Less frequent use of BIM during the construction phase confirms that in Canada, BIM is mainly adopted by architectural firms during the design phase. However, nearly three-quarters of the construction respondents were involved in at least one BIM project in the previous year.

Figure 4 sorts the primary uses of BIM as reported by the participants classified in three broad categories. The most prominent category of BIM applications

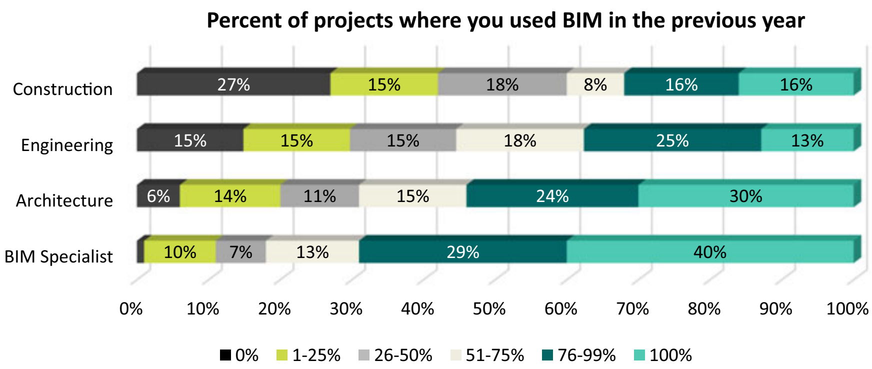

Fig. 3 Frequency of BIM projects among disciplines

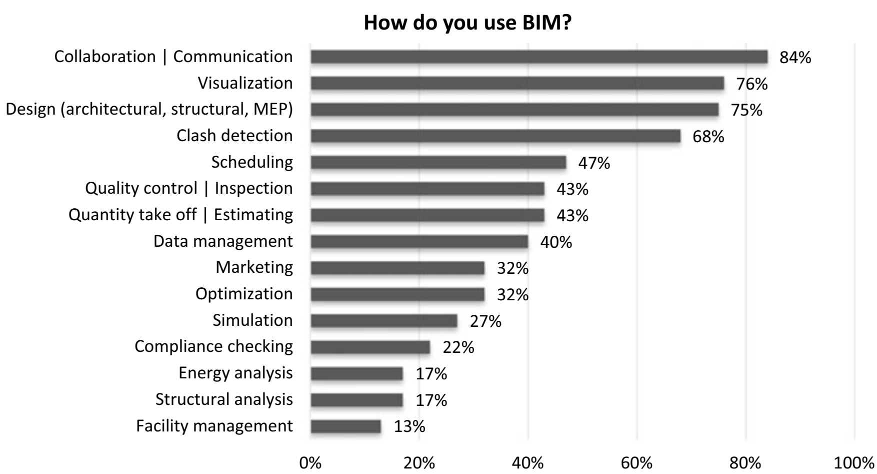

Fig. 4 BIM uses

Table 1 Main uses of BIM by discipline

Main uses of BIM	BIM specialist (%)	Architecture (%)	Engineering (%)	Construction (%)
Collaboration | Communication	100	85	76	68
Visualization	85	79		68
Design		89	83	
Clash detection	88		63	56

mainly engaged multiple stakeholders and spanned over a wide range of professions, including collaboration/communication, visualization, design, and clash detection (top four). The second well-known category of BIM applications is related to construction field applications, attracted by 40–47% of participants, namely scheduling, estimating, inspection, and data management. Perhaps the least exploited BIM applications are those that involve only single or very few stakeholders, such as optimization, marketing, and simulation.

Table 1 shows the top three uses of BIM among disciplines. BIM-specialists and construction participants reported collaboration/communication as their primary use of BIM. Architects and engineers, however, identified design as their top use of BIM. Clash detection was one of the top three uses of BIM among all disciplines except for architecture. Similarly, all but engineering chose visualization as one of their three main uses of BIM.

Introducing new technology to an organization is often challenged with resistance to change. Adoption of BIM in the construction industry is no exception, facing barriers at various levels. Figure 5 shows some of those barriers, where the black bars represent industry level barriers, the green bars indicate company level barriers, and the grey bars represent barriers to individuals.

Participants were asked how they envisage other technologies influencing the industry (Fig. 6). Virtual and augmented reality (VR/AR) had the highest potential impact, endorsed by 89% of participants. Seamless integration of BIM with these visualization technologies and recent advancements in cloud systems facilitate distributed and more intuitive interaction for all project stakeholders with BIM. Reality capture technologies, particularly laser scanning, were identified as the second most promising technology, driven by the need to capture the projects' quality and progress in real-time with accuracy and efficiency. E-permitting and automated code compliance checking also garnered more than 80% support from participants. Artificial Intelligence (AI) and machine learning, which have recently resulted in numerous start-up companies, were expected to grow substantially in the near future. Internet of things (IoT) and its potential to enable 5D BIM, by continuously monitoring the buildings' performance and integrating it with BIM, was supported by more than three-quarters of participants.

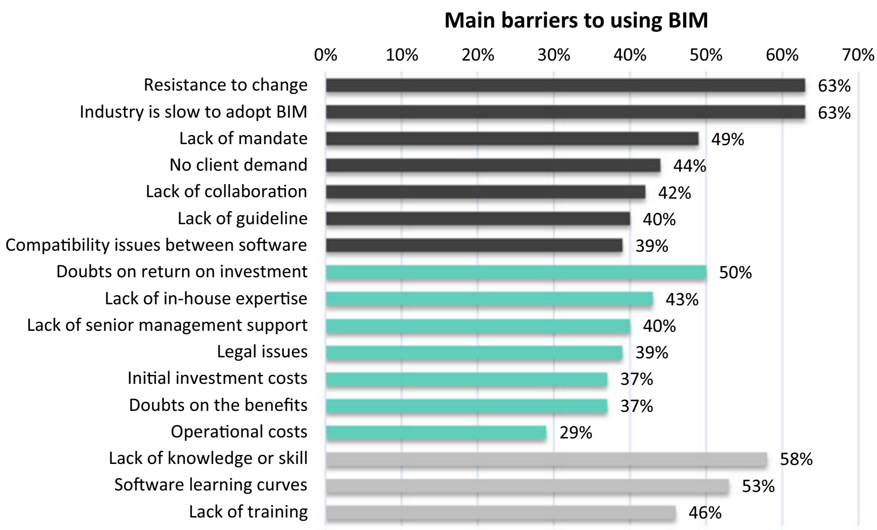

Fig. 5 BIM adoption barriers

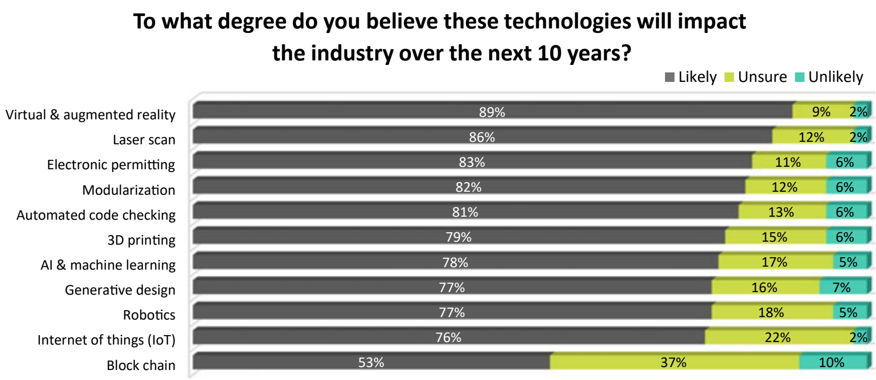

Fig. 6 Construction industry and future technologies

3 Manifestation of Problems in the Field

The use of BIM for field applications substantially increased over the past decade [26, 29], which is largely owed to the improvement in information and communication technologies (ICT), as well as the ubiquity of mobile computing devices [4]. Unlike design activities in an office setting and due to the dynamic nature of construction activities and the mobility required by field personnel to move around the job site, robust handheld mobile devices play a crucial role in bringing BIM to the site. Field personnel, however, are not often familiar with existing BIM software tools. Therefore, BIM applications with more intuitive user interfaces assist with increasing their use in the field. The key is to have those field BIM applications and original BIM files connected using cloud computing so that data generated, or changes made in one environment would immediately reflect on the other.

There are several features provided by BIM-to-field applications used to improve usability. These include model navigation to find and view a particular scene in 3D, filtering to remove superfluous information and view only those objects of interest, and the ability to cut sections or view the model from arbitrary angles not contemplated by the designers. It is also useful if the models link prefabricated components to manufacturer specifications, contain markup features, and allow users to measure between points [29].

To verify the survey findings and evaluate the feasibility of implementing BIM in the field, one of the authors attended regular coordination meetings focused on resolving site issues over three months. Interviews with the site superintendent, supervisors, and coordinators were also undertaken. The discussions yielded insights into the barriers of BIM adoption, common issues during construction, and how visualization technologies might improve field workflows.

The project, referred to herein as The Towers, involved two forty floor residential buildings under construction in Toronto. At the time the study began, shoring and excavation operations had been completed. The active trades were waterproofing foundation walls, installing under slab drainage, installing mechanical and electrical infrastructure rooms, and forming and casting concrete at the 1st and 2nd floor superstructure.

While the architectural model was available in ArchiCAD, the structural design was developed in 3D CAD, and the mechanical design was drawn in 2D CAD. There were eight sets of drawings: landscape, architectural, interior design, structural, mechanical, electrical, civil and site survey, and sprinkler system.

The design-related coordination meetings were biweekly and held inside a trailer on site. Although the primary design documents were 2D drawings, the site trailer was equipped with a large TV screen, which was used to show details or to share the most recent revisions if they had not yet been printed and delivered.

When the issues in the request-for-information (RFI) log were resolved, the relevant consultant would issue a site instruction (SI), update the drawings, and send them to the site coordinator. The consultants used Bluebeam software to annotate the drawings with a cloud box around the updated information. Then, the site coordinator printed out and delivered the drawings to the subcontractors to ensure that they always had access to the most updated drawings. The most common questions were about missing dimensions and insufficient space to install equipment. There were, on average, two construction issues reported each day; however, the number of issues per day was expected to increase significantly as the project progressed.

In general, BIM-enabled field applications fall into three categories [29]: (1) Visualization: making design information available, (2) BIM-supported site coordination, and (3) BIM-supported field data collection. Categories 1 and 2 directly relate to the top three BIM applications listed in Fig. 4. These application areas are explored in the following subsections and their manifestation in the field using information and observations from the construction site is discussed.

3.1 Visualization and Design Related Issues

The most frequent visualization issues at the Towers were related to mechanical, plumbing, ventilation, and building envelope systems. One common issue was the interference of mechanical components with each other and with structural elements, which could then cause headroom clearance problems. Resolving issues required all participants to have a solid understanding of the 3D configuration of the components. Since there was no 3D model for mechanical components and coordination was conducted on 2D drawings, effective resolution of these issues was heavily dependent on the participants' experience and visualisation capability. They often had to sketch the configuration to visualize it, hence helping all participants reach a unified understanding of the issue. The challenges with the visualization of 2D drawings are significant where the design is complex. For instance, The Towers ground floor was stepped with 12 levels, making it difficult to visualize. Such complexities can result in significant rework if not understood well prior to construction.

Another common issue rested on the dimensionless schematic mechanical and electrical design drawings. Only the architectural drawings had dimensions. According to interviewees, mechanical consultants rarely specify dimensions on their drawings and some mechanical components were not shown at all, such as pipe traps. To obtain the field's dimensions, the mechanical, electrical, and ventilation supervisors had to match the drawing with its corresponding architectural drawing and find the dimensions; the site manager used Bluebeam to verify some dimensions. Designing in BIM necessitates that all consultants, including mechanical and structural, specify dimensions and details. Therefore, making such a model available for the field crew enables them to collect some information that not found in their 2D drawings. Nonetheless, the fact that BIM requires significant effort to develop details is one reason why mechanical consultants are slower to adopt BIM.

The most critical problem in the design drawings, however, related to constructability and manoeuverability. The former is mainly because each system had its design drawings, making it challenging to identify clashes. BIM could allow all components to be in the same model, allowing automatic detection of clashes during design. Manoeuverability issues relate to figuring out if materials and equipment fit into the space allocated to them or if space exists to move them into their final location. For example, some pipes may be too big to fit into the hallway, which dictated the destruction of already built components. Although the 3D model does not automatically reveal manoeuverability problems, it improves the spatial perception of those who review the design documents and help them assess manoeuverability. Visualizing BIM in a VR environment can further improve this workflow as it gives a realistic full-scale representation of the design [3].

Sometimes there is a mismatch between the design specifications and its constructability. For instance, the doorframe specified a 200 mm extrusion profile; however, the fabricator could only provide 150 and 300 mm extrusions without refitting their equipment, which was costly. This design change had a domino effect, as it required changes to the edge of the slab and proximal elements in the architectural and structural drawings.

Reviewing the design prior to construction to identify inconsistencies is a tedious but critical effort that depends on the team's experience, attention to details, and completeness of drawings and specifications. These issues would be likely to be detected and resolved prior to construction if more subcontractors were involved during the design phase. Extensive pre-construction collaboration between design consultants and subcontractors is facilitated in integrated project delivery (IPD) projects where BIM is the centre of all communications [18].

3.2 BIM-Supported Site Coordination Issues

In addition to delivering design information to the field, BIM provides improved coordination capacity by allowing access to supply chain data [9]. Some BIM-to-field software applications offer customizable checklists to streamline site data collection workflow and link them with their respective objects in the BIM file. Integrating that with components having barcodes or QR codes allows reporting timely and rich information regarding the construction status. A cloud-based BIM further improves such workflows by facilitating real-time access of all participants to information and how it changes [29].

BIM also allows personnel to link their information to the model when creating RFIs or change orders to include physical information. BIM functionality to streamline coordination in the field is not limited to better design and issue resolution. It also improves coordination to assign space and time for the trades to perform their planned activities [23]. Having updated information about the site condition and current progress and the 4D model assist site managers in providing trades with information about their upcoming tasks and their constraints.

3.3 BIM-Supported Field Data Collection and Other Issues

The next application of BIM in the field is to improve data collection workflows during construction. There are several objectives for data collection during the construction phase of a project. These goals include collecting physical characteristics for quality control, remote visual inspection, progress tracking and verification, remote decision making, safety analysis, and environmental analysis [2]. To this aim, an extensive repository of data is generated during construction, such as as-built reports, schedules, construction methods, cost data, daily [progress] reports, site photos, site instructions, design changes, requests for information (RFI), and change orders [27]. The traditional approach in field data collection leads to having isolated silos of information. BIM offers a centralized data approach that allows data to be integrated with the central model. Besides, integration can occur in real-time.

Several studies and software tools exist to develop the necessary workflows for each application.

Many scheduling issues are raised as a typical construction schedule lack detailed information about the procurement of materials, availability of equipment and tools needed to install them, and resources needed by the crew. Regular coordination meetings with the trades help but do not fully address all issues.

- Procurement must consider lead times needed to manufacture and ship products to ensure their availability in time for their installation. Some components, such as window walls, have lead times of four to six months.
- Shared resources used by multiple trades, such as tower cranes and hoists, require detailed scheduling to minimize conflicts.
- Trades require space to store equipment and materials, but those components must be readily available when and where they are needed as the construction progresses. A practical site layout can improve productivity and safety [19], and BIM has been shown to improve site layout planning [14, 30]. Virtual reality is a promising tool in site layout planning as it provides a realistic visualization of spatial limitations in the field [35].
- Safety coordinators strive to address safety concerns before subcontractors start working in their allotted area. Numerous studies about BIM and VR/AR suggest that BIM can improve hazard identification and coordination of safety issues among project participants [10, 20, 37]

4 Conclusion

Based on the results of three surveys conducted nationwide in Canada between 2018 and 2020, BIM adoption lacks momentum in different phases of asset's lifecycle. Architecture firms are champions of BIM adoption in their practices; however, their effort is not fully exploited by their AEC/FM counterparts. Using BIM has proven cost savings for construction industries through early clash detections, but its potential cannot be fully utilized without all the stakeholders on board. Canada lacks government's mandate for using BIM for large projects; hence, the AEC/FM industry does not feel the urgency to overcome BIM implementation barriers.

Our case study, the Towers, is an example of common practice in Canada. The architect provides the Architectural BIM; however, drawings provided by other consultants are in 2D format. This inconsistency in delivering the drawing by different stakeholders created numerous issues manifested on the field and observed by the researcher. These issues were mainly related to visualization difficulties, clash detection, dimension ambiguity and identifying constructability of the original design. Site coordination and data collection during the construction were also proven to face challenges with state-of-the-art practices. Resource allocation strategies, site layout planning, material delivery lead time and safety precautions were also identified as practical BIM applications based on this particular case study, and therefore, great potential exists for new application development to facilitate such functionalities in the field.

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An Automated Approach to Generating Optimized Crane Mat Layout Plans

G. Ali, E. Tamayo, A. Mansoor, J. Olearczyk, A. Bouferguene, and M. Al-Hussein

1 Introduction

The concept of modular construction is that large-scale projects are constructed by splitting them into small components manufactured in a controlled environment. The modular construction approach is gaining attention in the building industry due to various interrelated issues with the cost associated with on-site construction [22]. Modular construction's more sustainable approach in terms of environmental, economic, and social factors serves as a significant driver of the adoption of modular construction [9]. In general terms, implementing technology to improve a process can reduce the resources required, and the integration of optimization techniques can reduce the amount of time the resources are utilized and reduce or eliminate any human errors and the corresponding rework that an error would require. The time saved can be used on some other constructive work. It is interesting to consider that a principal goal of optimization is to enhance sustainability [19]. The present study presents a novel approach to crane mat optimization on a construction site through mat layout plans/drawings. With the maturation of the modular construction approach, maximizing a module's functionality is becoming a more common practice, which leads to an increase in a module's weight, from tens to hundreds of tons. These large heavy modules have also increased the usage of resources involved in crane work, such as crane mats, rigging gears, assisting cranes, and trailers. It is equally essential to mention that ground stability is one of the most crucial issues in crane work. A study by Occupational Safety and Health Administration, USA, (OSHA) reported that, from 2000 to 2009 in the United States, approximately 50 deaths were caused

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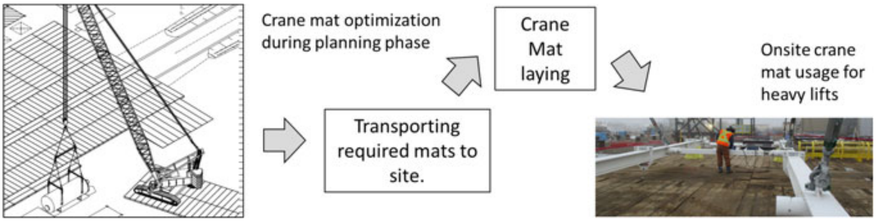

Fig. 1 Lifecycle of crane mat usage, from planning to utilization

by "Crane Tipped Over," a direct result of poor ground support [23]. Recently, 937 construction workers lost their lives at work, of which 505 (54%) correlated with crane work [11]. On the construction site, to ensure cranes can operate safely, the first order of business is to ensure the ground's soil bearing capacity can accommodate the pressure due to the crane's compounded weights and its payload. There are two ways to tackle this soil bearing capacity issue: (i) using compacted aggregate to increase the soil bearing capacity; and (ii) using layer(s) of crane mats to distribute the ground bearing pressure to make it equivalent or less to the soil bearing capacity. Considering crane mat utilization as a more economic and modular approach in comparison to compacted aggregate, this leads to the increased usage of crane mats on the construction site for all types of crane work, regardless of the ground condition. This burgeoning mat usage has necessitated mat layout plans/drawings for every instance of crane work on the construction site. Figure 1 illustrates the process of mat laying. The mat layout plan/drawing is prepared as per the crane usage on the construction site and indicates the number of mats required for each lift. These mats are moved by trailers from the mat yard to the construction site. Cranes or forklifts situate these mats on the ground as per the mat layout plan/drawing. After the crane work is complete, these mats are transported by trailers back to the mat yard.

Practitioners typically prepare mat layout plans using computer aided-design and drafting (CADD) software based on the construction site constraints. The most crucial constraint is to minimize the number of mats used on site and to cover the maximum area required. Another constraint is the laying process, as the on-site mat laying starts from one edge of the required mat area and continues until the required area is covered completely. The present study puts forward a novel automated approach to preparing crane mat layout plans/drawings based on these constraints and the mat layout requirements. Typically, it takes 20–30 min for a practitioner to manually complete the preparation of mat layout plans and drawings based on the aforementioned constraints, while the algorithm formulated in the present study automates the mat layout plan/drawing preparation and reduces the preparation time required to an amount of time measured in seconds. For demonstration purposes, the algorithm is developed in Visual Basic and employed as an application in Autodesk AutoCAD (2021). The developed algorithm is based on an agent-based greedy optimization approach, simulating a practitioner's behavior to prepare a mat layout plan/drawing. In the end, the algorithm provides details pertaining to the number of mats used, the area covered, the mat area, and the mat wastage in terms of surplus area covered. It is not uncommon for a practitioner to need to manually revise the mat layout plan/drawing numerous times in order to optimize for minimum mats with maximum area covered. Practitioners can avoid this rework by using this novel mat optimization algorithm to prepare the optimized mat layout plans/drawings on the first attempt.

2 Literature Review

The greedy algorithm is one of the most extensively used meta-heuristic optimization methods when the goal is to provide the optimal solution to complex problems, which are known to be time-consuming when tackled using deterministic manual methods [4, 6]. The greedy algorithm is an agent-based optimization technique to optimize the solution following a greedy approach by selecting the finest (best) scenarios at each state. Resource optimization using greedy agent-based optimization is not new. This approach can optimize dynamic ridesharing for the higher user cost-saving, and minimum vehicle kilometers traveled while allowing multi-passenger rides [16]. Not only that, but a greedy agent-based optimization approach can model evacuation traffic plans [15].

Many researchers have developed approaches to assist practitioners in the goal of optimizing site layouts [12, 17, 21]. In these approaches, some constraints such as safety, time, and costs are accounted for to figure out the best possible crane locations. Deen et al. [7] proposed a genetic algorithm approach for automated path planning of mobile cranes. Reddy and Varghese [18] also drafted a tool using configuration space (C-space) to discern the crane lift paths and optimize them within a constrained search space. These methods identify the space-occupying conflicts at discrete time steps and at every single location within a site's boundary. In such a case, site layout optimization can be time-consuming in large construction areas with several lifts in the plan. Crane optimization is a growing field of study in recent years due to computer simulation integration [1, 2, 13, 14, 20, 21]. However, research in the context of mat optimization is not apparent in the literature. When it comes to cost optimization, crane lift optimization is considered the main objective, but crane mat optimization can play a pivotal role in reducing the capital cost [3]. Practitioners usually provide the crane mat requirement on the construction site but overlooked the mat utilization in bulk [8, 10]. The research conducted by Taghaddos et al. [20] also examined crane optimization, including crane positioning, rigging gear optimization, lift optimization, crane path optimization, and crane mat requirements for the construction site, but omitted crane mat optimization. Considering this research gap, the contribution of the present study is an approach for the optimization of the crane mat layout with the integration of AutoCAD for the preparation of crane mat layout plan/drawing.

3 Methodology

In general, an optimization process is not a one-time process; instead, the overall process is reduced into smaller problems, and an agent-based greedy approach impersonating a practitioner's behavior is employed to optimize the mat layout using computer aided-design (CAD) software. To create the mat layout drawing manually, the practitioner undertakes the following procedure. First, the practitioner places the first mat based on practical constraints, as described in Sect. 3.1. After placing the first mat, the next mat is placed based on practical constraints around the first laid mat, as described in Sect. 3.2. The practitioner then places consecutive mats in the plan/drawing and proceeds until the last mat is placed in order to cover the entire area requiring mats for crane work. Figure 2 shows the mat layout procedure in sequence, starting from a location close to the pick/set point (payload pick and/or setpoint), until the crane mats fill the whole required area for crane work. The optimization process developed in the present study follows the same procedures and constraints (Fig. 2) to automatically prepare a mat layout plan/drawing for crane work. The overall optimization process is divided into two main parts as described in Sects. 3.1 and 3.2.

3.1 Algorithm Development: Placing the First Mat

To initialize the optimization process, the required area must first be selected with the assistance of CAD software to provide a set of cartesian points enclosing the area

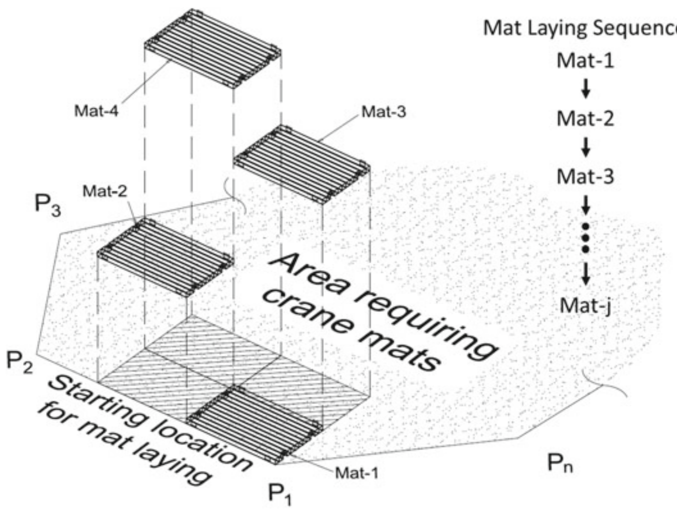

Fig. 2 Mat laying sequence

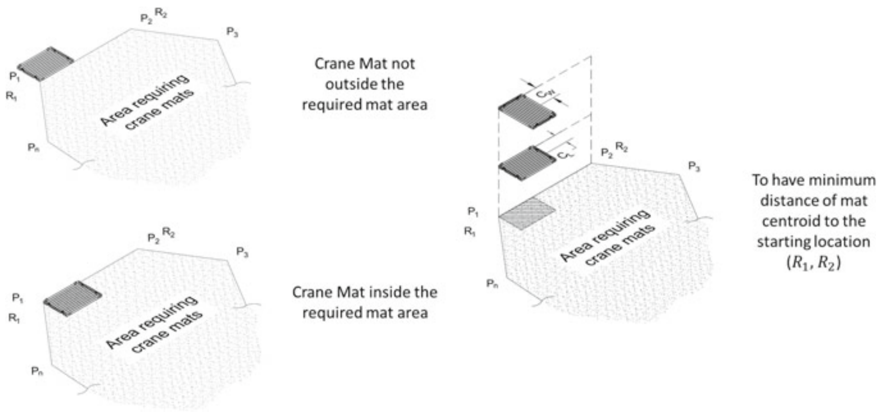

Fig. 3 The first mat laying conditions

required for crane usage and mat layout. Let $P_i(x_i, y_i)$, where $i = 1, 2, \ldots, n$, be the polygon vertices (area selected for the crane mat layout). Using the Surveyor's formula, Eq. 1 can be used to calculate the polygon area [5], or another method is to use a CAD program to calculate the area.

$$A_r = \frac{1}{2}\left|\sum_{i=1}^{n} x_i(y_{i+1} - y_{i-1})\right| \tag{1}$$

The next step is to indicate the edge from where the mat's laying will start, taken as $R_k(x_k, y_k)$, where $k = 1, 2$ and $R_k(x_k, y_k) \subset P_i(x_i, y_i)$. This edge acts as the starting location for the mat laying process. The optimization agent assigns the crane mat on R_1, parallel to the line joined by R_1 and R_2. The first constraint that the mat must be inside the required area, as shown in Fig. 3. The coordinates for the mats covering the required area are defined as $M_{hj}(x_{hj}, y_{hj})$, where $h = 1, 2, \ldots, n$ (number of mats) and $j = 1, 2, 3, 4$ (coordinates of each mat). Let Δ_h, where $h = 1$, be the area of the first mat placed on R_1 along with the line joining R_1 and R_2. The mat placement constraint (inside area) needs to follow that the intersection of these two sets Δ_h and A_r cannot be zero, provided that the mat is inside the required area, as shown in Eq. 2. In the case where the mat is outside the area requiring crane mats, the optimization agent flips and/or rotates (90°) the mat to place it inside the mat required area.

$$Mat\ Placement = \begin{cases} Inside & A_r \cap \Delta_1 \neq 0 \\ Outside & A_r \cap \Delta_1 = 0 \end{cases} \tag{2}$$

Mat laying on the construction site starts from an edge closer to the payload pick or set point, and the mats lay lengthwise to distribute the ground bearing pressure exerted by a crawler or hydraulic cranes. The approach is to place the mat with a minimum centroid distance from the line joined by R_k. Equation 3 calculates the centroid's distance from the starting line.

$$C_l \ or \ C_w = \frac{|aC_x + bC_y + c|}{\sqrt{a^2 + b^2}} \quad (3)$$

where C_l is the distance between the centroid (C_x, C_y) of the lengthwise mat and the line joining R_k; C_w is the distance between the centroid (C_x, C_y) of the widthwise mat and the line joining R_k; $a = R_{1y} - R_{2y}$; $b = R_{2x} - R_{1x}$; and $c = R_{1x}R_{2y} - R_{2x}R_{1y}$. Figure 3 shows that the optimization agent chooses the mat with minimum distance, which means if $C_l < C_w$, the lengthwise mat is selected, and if $C_l > C_w$, the widthwise mat is selected. After selecting the first crane mat, the area required for the mat laying decreases by $A_r \cap \Delta_h$. This depreciation also implies that the required area changes to A_{rh}, (where $h = 1$) using Eq. 4.

$$A_{r1} = A_r - (A_r \cap \Delta_1) \quad (4)$$

3.2 Algorithm Development: Placing the Succeeding Mats

After the laying of the first mat, the laying of the subsequent mat also follows certain site constraints. One constraint is that the next mat in line should not superimpose the previously laid mat (Fig. 4a). The easiest way for the algorithm to check is to calculate the previous mat's intersection with the succeeding mat and whether it is equal to zero or not. However, before that, the possible locations for the mat placement are required. The vertices of the already placed mat serve as the mat laying locations. Let $O_h(x_{hj}, y_{hj})$ be the list of the available locations for the mat placement. At this point, there is only one mat placed, resulting in four locations (vertices of the already

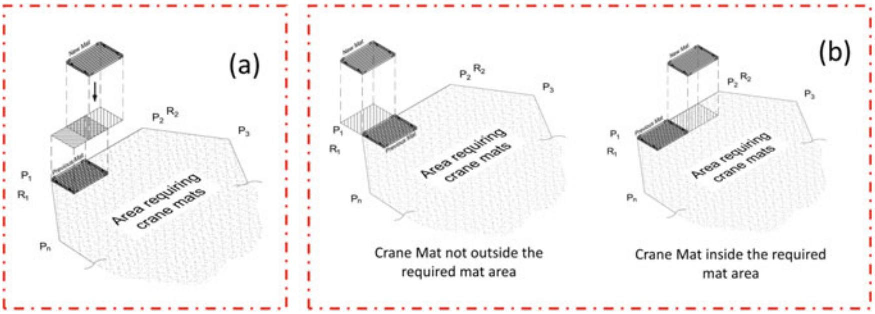

Fig. 4 **a** Mat superimposing constraint for next mat; **b** next mat placement constraint (mat inside the required area)

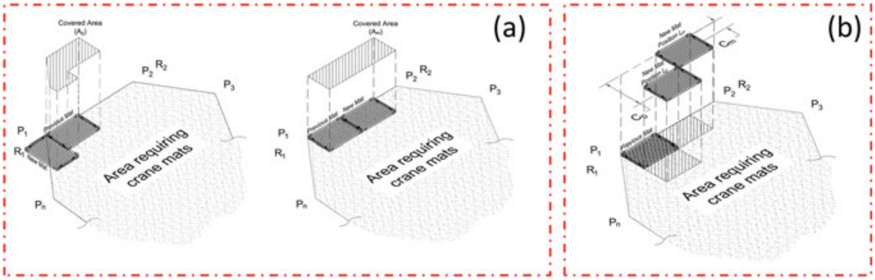

Fig. 5 **a** Maximum area covered constraint; **b** minimum centroid distance constraint for mat laying

situated mat) to consider for the next mat placement. As the number of mats increases, so does the number of locations on the list $O_h(x_{hj}, y_{hj})$ until the mats fully cover the required area.

The algorithm assigns the subsequent mat M_{2j} to every location in $O_h(x_{hj}, y_{hj})$. If there is no overlap of mats, the superimposing mat constraint $(A_r - A_{r1}) \cap \Delta_2$ should be equal to zero. The optimization agent moves to the next location if the selected location returns a result for $(A_r - A_{r1}) \cap \Delta_2$ that is not equal to zero. The next (second) constraint, following Eq. 2, is to check whether the succeeding mat is inside the required area or outside the required area (as shown in Fig. 4b). The value of A_r in Eq. 2 changes to A_{r1}, and Δ_1 changes to Δ_2. This rule escorts the fundamental idea to blanket the required area with the mats without wastage (overutilization and overcrowding of crane mats).

The constraints stated above for the second mat reduce the number of possible locations for the mat laying. The following two constraints (three and four) apply to the available possible locations: have the maximum area covered (see Fig. 5a), and have a minimum centroid's distance from the starting location (see Fig. 5b). Figure 5a compares two areas, A_o and A_m, projected by placing a mat at two different locations. The optimization agent selects the location with the maximum required area covered. Equation 3 performs the centroid distance calculation from the starting location. Here, the competition is between two locations, one with C_o and one with C_m.

The four constraints described above facilitate the process described earlier to find the succeeding mat's best location after laying the first mat. If two locations satisfy equally, the optimization agent selects the mat placement's first selected location. Later, after the second mat, the process repeats itself continuously to place the remaining mats. For each iteration, the list $O_h(x_{hj}, y_{hj})$ increases incrementally by four additional locations. The optimization agent visits each location (in the list) to find the best succeeding mat placement location and lays the mat accordingly. The iteration continues until A_r transmutes to A_{rh}, and decreases to half the single mat area. The optimization process terminates itself when the minimum number of mats for the job covers the entirety of the required area. In the end, the output of the optimization process includes the optimization details, i.e., the number of mats used, the area covered, the mat area, and the mat wastage in terms of surplus area covered.

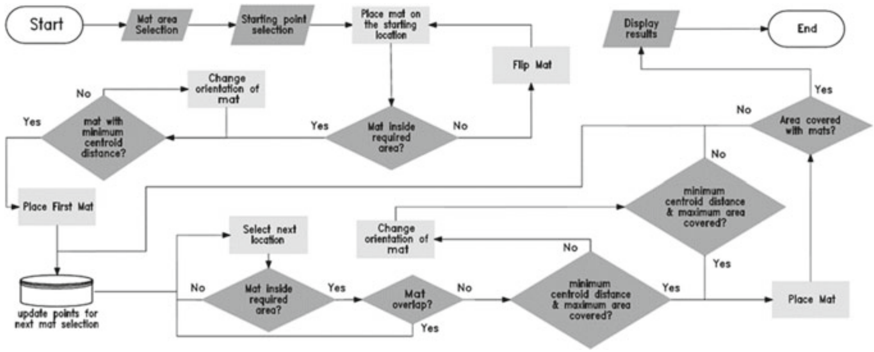

Fig. 6 Flowchart for crane mat optimization algorithm

Figure 6 shows the whole methodology as a flowchart for the data processing at each constraint and optimization location. The flowchart shows that the first mat placement is different from the rest of the mat placement, as the superimposing constraint does not apply to the first mat placement. After the placement of the first mat, all four constraints become active for the remaining mat placements.

4 Case Study

Any one mat size may be used in this agent-based optimization algorithm. For the purpose of the present case study, a mat size of 6 m × 2 m is the subject mat for optimization. A hypothetical industrial project plot plan is used as a case study for crane mat optimization for crawler crane usage. The assumption is that there are four areas requiring crane mat placement and optimization. For the optimization process, the algorithm is initiated on each area separately. The developed algorithm is executed individually for each required area to prepare the layout plan. Figure 7 shows the procedure performed for the mat optimization for one type of mat. Initially, the polygon (the area required for the mat laying) is selected (by the practitioner). The subsequent step practitioner is to select the starting location (payload pick or setpoint). Next, the algorithm starts placing the mats in a sequence, according to the procedure described in the methodology section. After placing the first mat, the optimization proceeds to the next mat selection (Fig. 6). The algorithm performs the same selection routine to identify the locations of the mats required to cover the remaining area. At the end of the optimization process, the outcome includes the required area, the number of mats used, the area covered, mat wastage, and the remaining area. The same procedure is performed on all four separate areas to cover them with crane mats. Figure 8 shows the empty area and the algorithm's filled area (with the crane mats) for all 4 areas of the hypothetical industrial project.

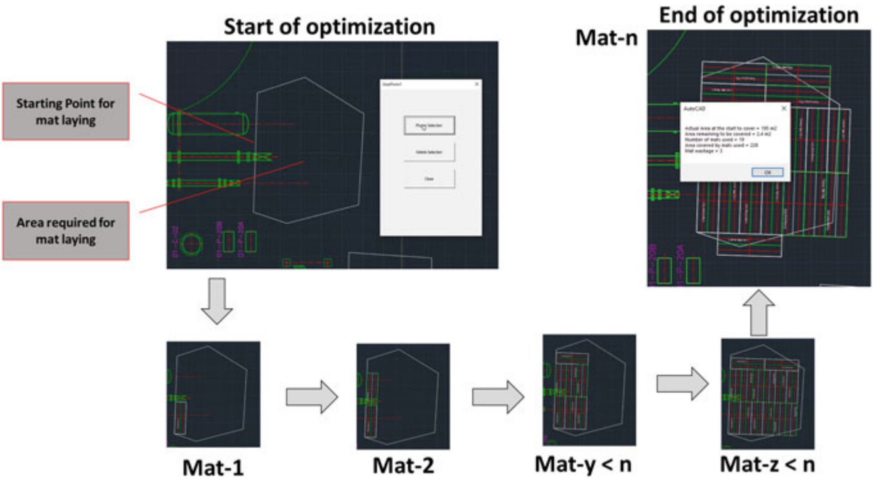

Fig. 7 Sequence for the mat optimization (for one size of mat)

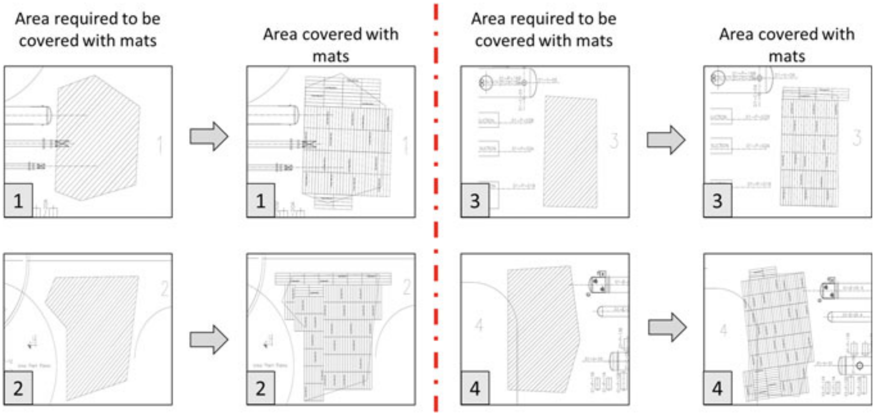

Fig. 8 Crane mat optimization case study examples 1–4

5 Outcome and Discussion

The run time of the optimization increases as the number of locations, $O_h(x_{hj}, y_{hj})$, increases by four with each new mat placement. The algorithm surveys all the cartesian locations in the list $O_h(x_{hj}, y_{hj})$ to check each mat's placement. For Case-1, the first mat placement time is 0.5 s (number of locations = 1), but for the last mat, because there are 76 possible mat placement locations, it is 4.3 s. Figure 9 shows the selection time for the placement of the mat and the number of possible mat placement cartesian locations for each mat number. The total time required for the optimization and drawing preparation is 38.8 s, which represents significant time savings for

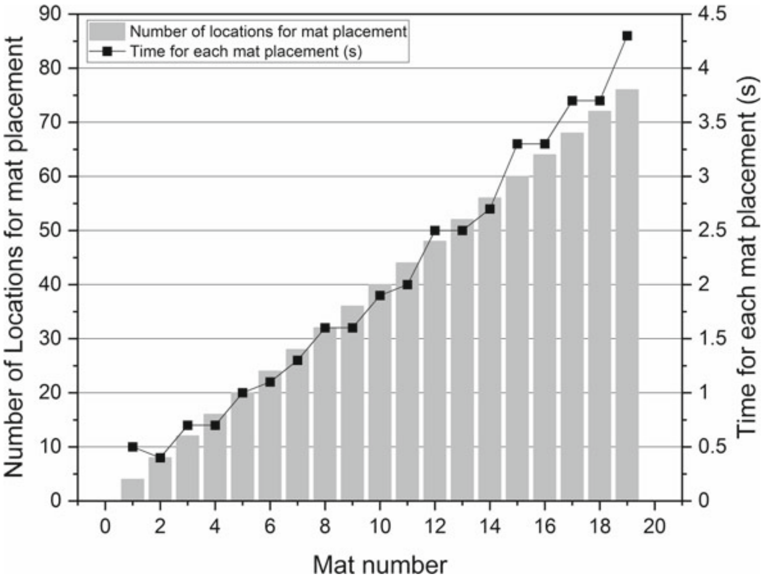

Fig. 9 Number of possible locations and time for each mat selection along with mat number (Case-1)

the practitioner. Typically, the preparation of this type of drawing takes 10–20 min for a practitioner to accomplish. However, the developed application takes 38.8 s to complete the same task, imitating a practitioner's mat selection and placement behavior.

Figure 10a shows the time required to complete each case study example vs. the mat sequence number. All four case study examples show that the time required to determine the next mat placement increases with the placement of each subsequent mat. Table 1 shows the detail for each case study example. For Case-4, the time required by the algorithm to finalize the optimization is 84.3 s. Case-4 has the largest area required (312.2 m^2) to be covered with the mats. The total number of mats used for Case-4 is 29, making the total area covered 348.0 m^2. The mat wastage is equivalent to approximately three mats.

The next question is to determine the average amount of time required for each mat placement. Figure 10b shows the average time in seconds per possible mat placement location for each of the mats placed. For Case-1, Case-3 and Case-4, the trendline shows that the average time increases, but for Case-2, the trendline decreases.

Advancements in optimization processes can save much time and eliminate human errors. The automation of the mat layout plan/drawing process may in the long run reduce resource usage and wastage. Work that usually takes hours to complete can be accomplished in minutes with the adoption of the mat optimization algorithm for the preparation of mat layout plans/drawings. The outcome in terms of the number

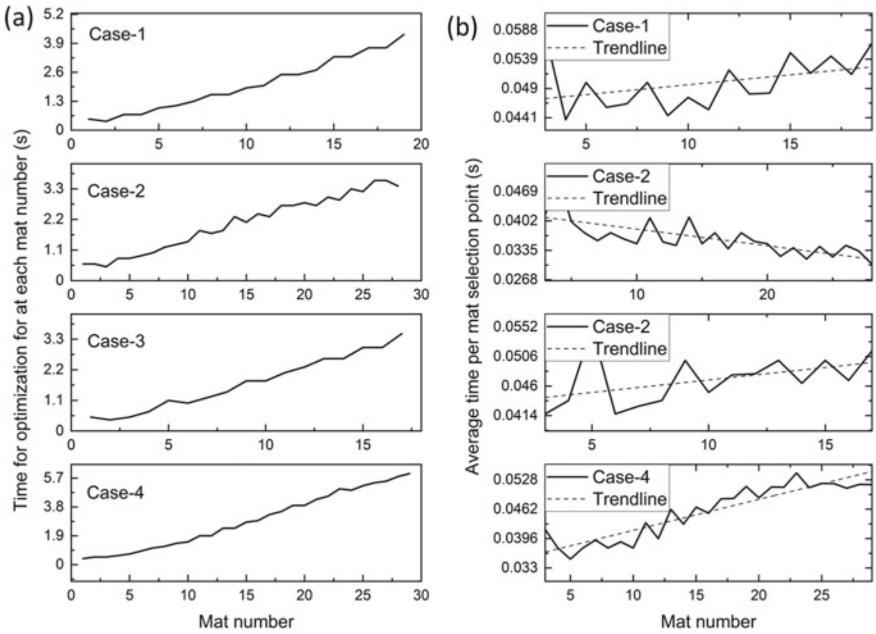

Fig. 10 **a** Time required for each mat selection along with mat number; **b** average time per mat placement and the trendline along with the mat number

Table 1 Details of the 4 case study examples for the mat optimization

Description	Case-1	Case-2	Case-3	Case-4
Actual area required (m^2)	195.0	308.6	195.7	312.2
Area remaining (m^2)	2.4	3.1	5.4	4.0
Mats used	19	29	17	29
Area covered (m^2)	228.0	348.0	204.0	348.0
Mat wastage	3	3	1	3

of mats used provides the practitioner with the exact resource requirement for timely planning and on-site execution.

6 Recommendations for Future Work

The methodology presented in this contribution offers the potential for further refinement; for example, by employing a neural network to trim the number of mat placement locations. Presently, each iteration examines every mat placement cartesian location repeatedly, even if it is rejected on the first attempt; therefore, the time required to accomplish the mat layout can be reduced further by employing a neural network to shorten the list $O_h\left(x_{hj}, y_{hj}\right)$.

In the present study, the optimization algorithm uses only one mat size. The use of various mat sizes for a single required area can decrease mat wastage (overutilization and mat crowding). The authors believe that the next phase of this research could include implementing various mat sizes for a single area requiring crane mats. The authors expect that the time required for computation will increase, but this will decrease the mat wastage, making it more resource sustainable. Another strategy to optimize the mats on the construction site could be the use of reinforcement learning. The authors believe that using reinforcement learning could reduce both the time required and the mat wastage in the long run.

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An Automated Mobile Crane Selection System for Heavy Industrial Construction Projects

R. Azami, Z. Lei, R. Hermann, and T. Zubick

1 Introduction

Safer work environment, lowered energy consumption, time savings, quality improvement, and waste reduction have convinced contractors over the past few decades to select off-site construction methods rather than on-site [6, 13, 18]. One of the challenges during off-site (modularized) construction is lifting modules, especially in heavy industrial projects where the number of the modules and their dimensions are greater than other projects. A primary method of installing modules on-site in industrial projects is to utilize mobile cranes. Mobile cranes lift the prefabricated modules from their pick location to the set point. Successful lifts require careful and accurate lift planning [17]. Project costs might increase, and schedule conflicts arise if errors happen in lift planning. Crane location, crane selection, support system design, motion planning of mobile crane operations (crane lifting path planning), are all a subcategories of the lift planning system [5]. In the current crane selection approach, lift engineers usually use tabular charts that are provided by the crane manufacturers, their experience of the past projects, and their engineering judgement to select the best crane for a project. This approach, however, may not lead to the best solution and sometimes fails which increases the cost of the project substantially. In this paper the authors reviewed the different methods presented by previous researchers for crane selection and proposed and algorithm for near optimal crane selection by implementing machine learning and heuristic techniques. This paper is

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organized as follows: Sect. 2 provides a brief review of the most relevant literature; Sect. 3 describes the methodology adopted in the current study; Sect. 4 provides a detailed case study; Sect. 5 presents the conclusions of this study.

2 Literature Review

Mobile crane planning can be categorized into different subtasks such as crane type and operation location selection [11, 12, 22, 23], crane lift path planning [2–4], crane productivity improvement and equipment design [9, 10, 16] and visual simulation of crane operations [7, 14, 24, 25]. Among these crane planning components, crane type and operation location selection aim to determine the most suitable crane under given constraints. Crane manufacturers produce capacity charts for cranes, whereby cranes are selected to operate. These capacity charts consist of different types of information, based on the lift method. Some examples of this information would be boom length, boom angle to the ground, lifting radius, lifting height, jib length, as well as its offset from the main boom centerline. Different lifting radii result in different lifting capacity for a crane with a given main boom/jib length. Adding a new section to a lattice boom or extending a hydraulic boom can change the boom length [1]. Considering all the crane models and constraints of a project, the process of lift planning can be tedious, and all the configurations may not be considered if performed manually by practitioners or lift engineers. It is prone to error because a typical industrial project usually consist of more than 100 modules and for each module a lift plan must be prepared [15].

Selecting the crane based on the heaviest and/or largest lift radius and identifying the potential crane and pick location by using the experience of the lift engineer, is an alternative method exploit for lift planning. The aforementioned methods are neither time saving nor cost-effective. Therefore, over the past few decades, researchers have introduced several methods for selecting and locating the most suitable crane for each project [22]. Single-crane location optimization modeling, which consider the total transportation cost between the crane and construction supportive facilities as the main criterion was introduced by Rodriguez-Ramos and Francis [21]. Based on factors such as site condition, building design, economy, capability, and safety, a fuzzy logic approach has been utilized by Hanna and Lotfallah [8]. However, their method lacks the crane model or a specific configuration. An artificial intelligence technique utilizing a neural network is used by Sawhney and Mund [23] to introduce a crane type selection tool called IntelliCranes [23]. Their method can provide both the type and model of the crane for a project, but they did not consider the duration of the project or the associated cost for each crane in their research. Other techniques such as 3D visualization have been integrated by researchers to validate the crane selection results and provide a visual representation. An algorithm, by which an optimal crane with respect to lift capacity has been selected and visualized by 3D animation, introduced by Al-Hussein et al. [1] and Moselhi et al. [19].

Wu et al. [27] developed an algorithm for selecting mobile cranes; similar to previous works, many factors are considered in their study, such as the lifting capacity and geometrical characteristics of the crane. In addition, they have considered the ground bearing capacity and then the selection is incorporated into a 3D computer-aided system for simulation, design, and rigging calculation purposes. Since each crane manufacturer publishes the capacity charts and geometrical characteristics of the cranes in different formats, utilizing these charts in the crane selection process makes it more time consuming. Previous researchers have introduced a comprehensive database called D-CRANE to support efficient selection of cranes [19]. Another widespread problem that arises during modular construction is the dynamic environment of the site job, which needs to be considered during the lift planning. In this regard, Olearczyk et al. [20] have developed an evolutionary algorithm that reacts to dynamic changing site conditions. Moreover, they have extended the boom clearance algorithm to consider the situation where the crane boom position is not in the normal plane, but in the inclined roof shape of the building structure [20]. By reviewing the literature, the authors realized the gap in the crane selection process as the lack of a decision support system that proposes the near optimum mobile cranes by taking into account the safety and the economical parameters of the projects simultaneously. The results of this research are beneficial for almost everyone who is involved in the project, since it decreases the cost and schedule and increases the safety of the heavy industrial projects. Moreover, it can be integrated with another heavy lift application called Automated Crane Planning and Optimization (ACPO) that has been developed for PCL to automate the process of checking the capacity of a crane and the clearances of the crane [26].

3 Proposed Methodology

The proposed algorithm is shown as a flow chart in Fig. 1. The application starts with connecting to the database, which in this case is an MS Access database. However, this database can be any type of relational databases such as SQL or Microsoft Excel. As the connection is made, the user can interact with the details of the projects and the modules that are already defined in the database or create a new project and add new modules to that project. The main process of the algorithm has been elaborated in the following sections.

3.1 Module Clustering

One of the paramount algorithms to cluster data is the K-Means Clustering, which is a powerful unsupervised algorithm to cluster large amount of data. By implementing such algorithm, the user has the ability to cluster the modules based on the number of the cranes that are available on the job site. The first input parameter for the algorithm

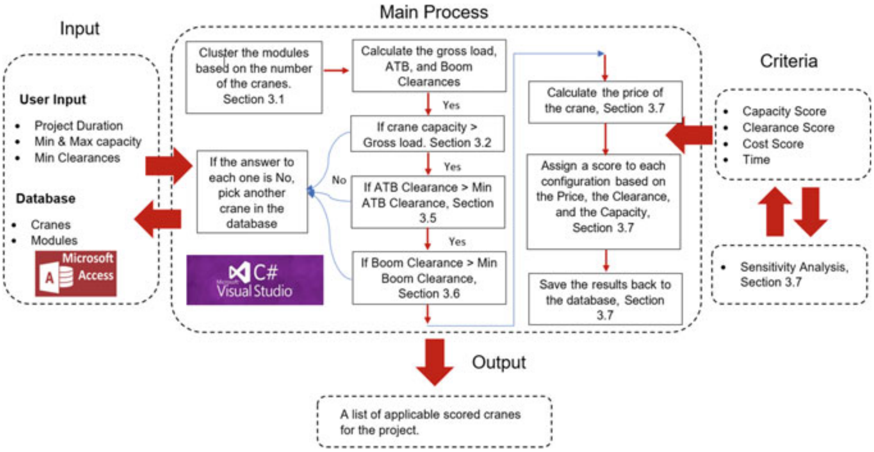


Fig. 1 Methodology for crane selection

Fig. 2 Pseudocode for k-means algorithm

```
Initialize clustering
loop until done
  Computes mean of each cluster
  Update clustering based on new means
End loop
```

is the height of the module plus the set elevation, which shows the overall height that the module needs to be lifted. The second parameter is the moment generated by the module, which is determined by multiplying the weight of the module by the set radius. The following pseudocode shows how the algorithm works. Based on the procedure described above, Fig. 2 provides the pseudocode for the algorithm used to cluster the modules.

3.2 *Crane Load Capacity Check*

The gross load, which consist of the weight of the module and the associated rigging and hook block, must not exceed the reduced crane capacity, which is calculated satisfying Eq. 1 The values of these weights are imported from the database or captured through the interface. This paper utilizes a methodology similar to [27].

$$\mathrm{SF(CC)} \geq \mathrm{GL} = \mathrm{W_m} + \mathrm{W_h} + \mathrm{W_r} \tag{1}$$

where CC is the total crane capacity provided by the crane manufacturer, GL is the gross load, W_m is the module weight, W_h is the hook block weight, and W_r is the rigging weight stored in the database.

The term SF in the Eq. 1 limits the crane operation to a certain percentage of its capacity, which should be lower than 1. The safety factor varies project to project and the user is able to change it through the interface.

3.3 Working Radius

The working radius has a direct effect on the crane capacity. The tip of the boom must reach both the lift point and the set point in order to lift and set the module. Therefore, the working radius, W_R, must be greater than the maximum of lift and set point radius as shown in the Eq. 2.

$$W_R \geq W_R^{'} \tag{2}$$

where $W_R^{'} = \max(R_L, R_S)$; R_L = distance from the center of rotation of the crane to the lifting point; and R_S = distance from the center of rotation of the crane to the set point.

3.4 Lifting Height

Lifting height, which is another influential factor affecting the module lifting process, is calculated for different configurations based on the following methods.

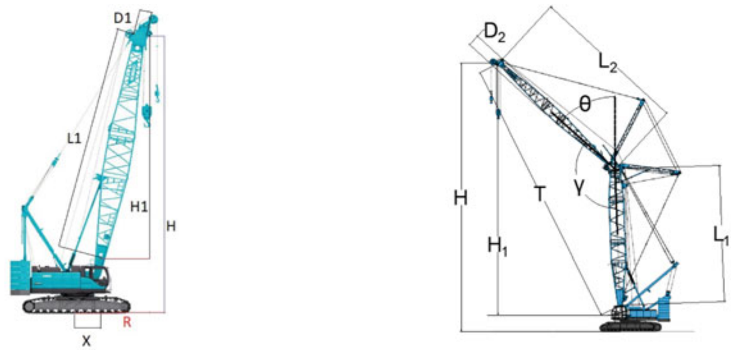
3.4.1 Main Boom Configuration

The height of the main boom shown in Fig. 3a has been calculated as following while the crane does not consist of any type of jib Eqs. 3 and 4.

$$H_1 = \sqrt{\left(L_1^2 + D_1^2\right) - (R - X)^2} \tag{3}$$

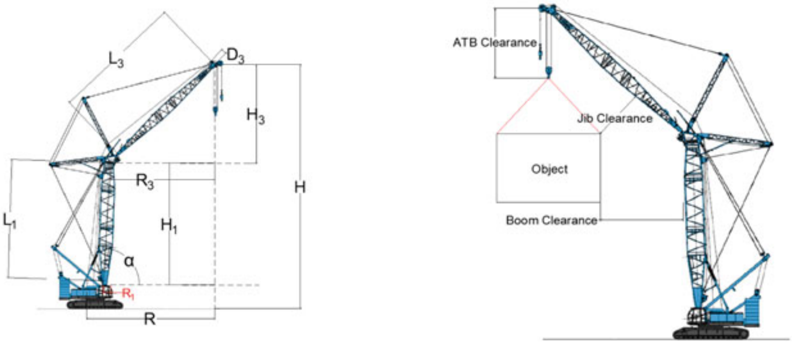
$$H = H_1 + Y \tag{4}$$

where (X) is the distance between the main boom foot and the center of rotation of the crane, (Y) is the distance between the main boom foot and the ground, (L_1) is the length of the main boom, and (D_1) is the main boom offset.



(a) Main boom configuration (source: kobelco-cranes.com)

(b) Fixed jib configuration (source: deldencranes.co.uk)



(c) Luffing jib configuration (source: deldencranes.co.uk)

(d) Boom and jib clearance (source: deldencranes.co.uk)

Fig. 3 Crane configurations

3.4.2 Main Boom with Fixed Jib

Jib is usually added to the main boom to increase the lifting height. Fixed jib refers to a type of jib that the angel between the main boom the jib if fixed Fig. 3b. However, the angle of the main boom and the horizon can change in a certain range Eqs. 5–8.

$$\gamma = 180 - \theta - \tan^{-1}\frac{D_2}{L_2} \tag{5}$$

$$T = \sqrt{L_1^2 + \left(L_2^2 + D_2^2\right) - 2 \times L_1 \times \sqrt{L_2^2 + D_2^2} \times \cos\gamma} \tag{6}$$

$$H_1 = \sqrt{T^2 - (R - X)^2} \tag{7}$$

$$H = H_1 + Y \tag{8}$$

where D_2 and L_2 represents the vertical offset of fixed jib and the fixed jib length.

3.4.3 Main Boom with Luffing Jib

A Luffing jib is installed on the main boom for the same purpose as fixed jib. The difference is that in this situation the angle between the main boom and the jib is not fixed, and the angle between the main boom and the horizon is fixed Fig. 3c. In this case lifting height is calculated as following.

$$R_1 = L_1 \times \cos\alpha \tag{9}$$

$$H_1 = L_1 \times \sin\alpha \tag{10}$$

$$R_3 = R - X - R_1 \tag{11}$$

$$H_3 = \sqrt{\left(L_3^2 + D_3^2\right) - R_3^2} \tag{12}$$

$$H = Y + H_1 + H_3 \tag{13}$$

where α = main boom angle, L_3 = luffing jib length, and D_3 = vertical offset of the luffing jib.

3.5 Anti-two Block Clearance

Anti-Two bock (ATB) is a piece of device that is hanging from the tip of the boom and prevents the hook block from being hoisted all the way to the boom tip. The moment that the module touches the ATB, the crane stops working Fig. 3d. Therefore, a clearance must be considered between the module and the ATB using the Eq. 14.

$$H_{hc} = H + A - ME + GE - H_R - H_M - H_{ATB} \tag{14}$$

where H_{hc} = is the clearance between the ATB and the hook block, H = lifting height, A = is the distance between the center of rotation of the crane structure and the ground surface, ME = is the module elevation, GE = is the ground elevation, H_R = is the height of the rigging, H_M = is the module height, and H_{ATB} = is the distance between the tip of the boom and the ATB devise. All the values are available in the database except the lifting height which was calculated in the previous steps.

3.6 Boom and Jib Clearance

In order to prevent the collision between the module and the boom or the jib, the minimum distance between the module and the boom or the jib is calculated in three-dimensional (3D) space Fig. 3d. The minimum clearance can be defined by the user through the interface and comparing with the calculated distance by the algorithm. The minimum distance between the module and the crane is occurring when the module is at its highest elevation. Therefore, the maximum height that the module can be lifted is determined through the process explained in Sect. 2.3. Next, the coordinates of two points on the module and two points on the main boom or the jib are determined. Each pair of coordinates is used to pass a line through them. Having determined the coordinates and the lines passed through them, the minimum distance between the module and the boom/jib is the length of the line segment that is perpendicular to both lines Eqs. 15 and 16.

$$(P_a - P_b).(P_2 - P_1) = 0 \tag{15}$$

$$(P_a - P_b).(P_4 - P_3) = 0 \tag{16}$$

where P_1 and P_2 are the coordinates of the two points on the module, P_3 and P_4 are the coordinates of two points on the boom/jib, P_a is the coordinate of a point on the line that passes through P_1 and P_2, and P_b is the coordinate of a point on the line passing through P_3 and P_4.

3.7 Score and Rank the Results

Based on the results of the previous steps, the algorithm displays the results to the user which includes all the passed and failed configurations and the reasons for each failure. However, these types of results may not be useful for the user as it does not show which crane is the best one for the project. To solve this problem, the algorithm first finds the cranes which can lift all the modules selected by the user and then based on the following criteria, it scores each configuration. Within the crane selection process for each project there are quite a few parameters that needs to be taken into account cost, project duration, super-lift capacity, boom/jib clearance, ATB clearance, and the percentage capacity have all been considered in this study. Each parameter gets a weight based on the influence that it has on the project (see Table 1). After consulting with crane experts and running sensitivity analysis to determine

Table 1 Ranking parameters and weights

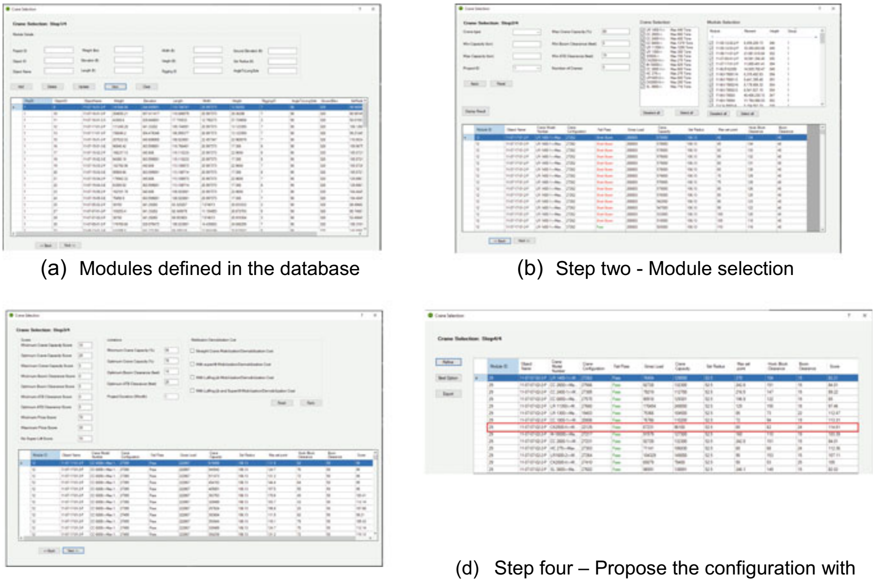
Criteria	Impact
Minimum crane capacity	10
Optimum crane capacity	20
Maximum crane capacity	5
Minimum boom clearance	0
Optimum boom clearance	5
Minimum anti-two block clearance	0
Optimum anti-two block clearance	5
Minimum price	35
Maximum price	70
Super-lift	10

the effect of each parameter on the crane selection, the following weights have been assigned to each parameter as a default value. However, the user is able to change them for each project.

4 Case Study

An actual case presented in this section to illustrate the effectiveness and practicality of the proposed algorithm. This case involves 86 different modules, which have been predefined in the database. In addition, 13 different models of mobile cranes consisting of nearly 35,000 different configurations were available for this project to be selected, all of which are stored in the database including the geometrical details, capacities, and prices. Figure 4a shows the first step of the application where the user can add/modify the modules using the available options. In the second step Fig. 4b the user can limit the search range by using the tools provided. After filling out all the textboxes and the dropdown lists, by clicking on the "Apply" button all the available cranes and modules associated with the selected criteria shown to the user in two different check list boxes. The user can select any combinations of the cranes and the modules provided in the check list boxes. The module selection check list box in the second step shows how the modules are clustered into different groups by using the moment and height as inputs of the algorithm. The number of the groups is defined by the number of the cranes that the user provides. The moment determined by multiplying the weight of each module by the set radius. The generated moment by any module provides a more understandable perspective to the lift engineers to select cranes rather than using the weight and the set radius individually. The next parameter is the height which shows the total height that the module needs to be lifted from the ground elevation to the set point plus the height of the module.

By clicking on "Display Results" the preliminary results are shown as a table to the user. This table shows all the details of the cranes and the modules selected



(a) Modules defined in the database

(b) Step two - Module selection

(c) Step three – Score the results

(d) Step four – Propose the configuration with highest score

Fig. 4 Case study results

by the user. One of the main problems that may arise with this table is that the user is not able to realize which crane is better, as this table just shows fail or pass. To resolve this issue the user can move forward to the next step where the scoring system is implemented. To accomplish this step, 10 criteria have been considered Fig. 4c. Minimum, optimum, and maximum crane capacity score has been defined to differentiate between the cranes based on the amount of the capacity of each crane that is utilized. The maximum crane capacity threshold was defined in the second step as it is a required value for the preliminary results and the associated score was defined as 5 (i.e., if 80% of the capacity of a crane is utilized, that crane is getting 5 points). The minimum and the optimum threshold were defined in the third step as 55% and 70% and the score associated with them are 10 and 20, respectively. For any crane with utilized capacity between these ranges the scores is distributed linearly. The next score is related to boom and ATB clearance. The threshold for the minimums has been defined in the second step and the optimum in the third step for the same reason as the maximum crane capacity. Minimum and maximum price scores are related to price of each crane. The algorithm first loop through all the cranes and find the maximum and minimum prices, then it assigns the associated score to each one and for the remaining cranes similar to previous steps the scores is distributed linearly.

Super-Lift is an optional piece that can be added to some configurations to increase the power of the crane and consequently increase the working radius of the crane. Adding a super-lift, however, is increasing the price of the crane as it needs ground preparation, manpower, and mobilization and demobilization cost. Therefore, a textbox was provided so that the user can enter a score for cranes without a super-lift in order to differentiate between the cranes with and without super-lift. As the prices of the cranes in the database are per-month, a textbox was created to get the duration of using the cranes per-month from the user.

The last part in this step is the cost of mobilization and demobilization of the cranes. This part provides the user the ability to consider the cost of the mobilization and demobilization of the cranes in the projects. Moreover, the user can change the number of mobilization and demobilization occurrence, which affects the cost of the project. By considering all the criteria and analysing them, the final results is printed as a table Fig. 4d. This table consist of the configuration of a crane that received the highest score. Based on this table, the lift engineers can decide to select the configuration with higher score.

5 Conclusion

This paper proposes a heuristic approach that automatically selects the near optimum mobile crane configuration in heavy industrial construction projects. A Machine learning algorithm—K-means—has been implemented to group the modules based on their moments and heights. Parameters such as the project duration, the cost of the crane, the safety, and the percentage capacity of the cranes were considered in this approach. The lifting capacity check and clearance check are the first steps of the algorithm. Following this step, each configuration, which passed all the criteria, is receiving a score. The weights that applied to each parameter were determined based on sensitivity analysis and consulting with lift engineers. The user is able to change weights for each project. This application can be a useful tool for both the engineers and the workers on jobsite and the facility owners since the safety increases and the cost and the schedule of the project decrease. This application has been developed based on relational databases such as MS Access, however; the code can be modified easily to be used with any other databases such as Microsoft Excel. Besides, the application can be utilized for mobile cranes, while it can be modified by the user to based for other types of cranes as application is based on a generic method. Finally, a case study is presented to illustrate the effectiveness of the application. For future research, this application can be improved to incorporate all types of cranes such as tower and derrick cranes. A 3D visualization can be added to the application for clash detection.

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Supply Chain Optimization to Gain a Competitive Edge in the Construction Industry

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1 Introduction

In the 2018 International Construction Market Survey report [26], the report authors are optimistic about a significant increase in global construction volume due to the 3.9% growth in global gross domestic product (GDP) forecast by the International Monetary Fund (IMF) [18]. However, there is a scarcity of skilled construction workers in 27 out of 46 surveyed markets, and increasing material costs are collectively driving up the overall cost of construction projects. This raises a flag for the industry to think ahead and strategically plan to address the fast-approaching financial challenges, and to avoid some serious profit margin erosions and ensure sustainability. Due to the increasing demand for skilled workers, materials, and equipment, the average forecasted construction cost increase for the 46 markets is 4.3% for 2018, compared to an average of 4.1% for 2017. Inevitably, project preliminaries and material costs have impacted profit margins and will continue to do so;

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the forecasted global average profit margin is 6.4%. The report further discloses the fact that construction businesses in North America, on average, work at profit margins of 7% or lower and spend up to 13% on account of preliminaries. Potential changes to the North American Free Trade Agreement (NAFTA) and hikes in interest rates may mount further pressure on the construction industry in Canada, where, on average, in 2017 labor costs increased by 2%, overall cost escalation was 3%, preliminaries account for 10%, and organizations work at 6% profit margins [26]. All previous research studies on the subject of purchasing, sourcing, procurement, strategic procurement, materials management, or supply chain in the construction industry, while covering the part of material and equipment acquisition, have mostly focused on contract types, on the timing and method of involving suppliers on projects, and on making the sourcing function effective from a control standpoint. Conventionally, early supplier involvement is encouraged to offset schedule delays. When a surge of new projects is expected and a shortage of skilled trades is a reality, the unbalanced supply and demand of the labor force will naturally push overall project costs up and erode profit margins and negatively impact the bottom line of organizations in the industry. Procured materials, equipment, and services on industrial projects account for approximately 65% of total project cost and a return on these extensive investments must be realized by deploying the most advanced sourcing techniques, which are the key characteristics of world-class supply chain management (SCM) functions at world-class manufacturing facilities, and at a few of the very large multinational engineering-procurement-construction (EPC) organizations [24].

The objective of this paper is to understand the as-is state of materials management, and more specifically, to identify the gaps between the materials and services acquisition practices in the construction industry and the proven world-class practices embraced by global multinational organizations in the manufacturing industry in order to identify and propose modern and innovative technique(s) with estimated potential benefits. Moreover, the objective of the present study is to make recommendations as to the need for further study and research on how the innovative approaches can be tailored to fit and benefit the construction industry in general.

2 Methodology

Globally, supply chain and procurement best practices, irrespective of industry, are advocated by the following world-class professional supply chain organizations (hereafter termed as "professional bodies"):

1. Chartered Institute of Procurement and Supply (CIPS) (https://www.cips.org).
2. Institute for Supply Management® (ISM®) (https://www.instituteforsupplymanagement.org).
3. Centre for Advanced Procurement Strategy (CAPS) Research (https://www.capsresearch.org).

Fig. 1 The sequential method for comparing supply chain practices

4. American Production and Inventory Control Society (APICS) (http://www.apics.org).

The Construction Industry Institute (CII) has also done significant research work and developed the best practice guidelines specifically for the construction industry to meet the project-based needs related to procurement, logistics, and field inventory management. In addition, independent researchers' work in construction materials management also contributes significantly to the field. For ease of expression, the professional bodies, the CII, and the independent researchers in this field are hereafter termed collectively as the 'three sources'.

In this paper, knowledge segment refers to one full package of skills, tools, or techniques used by supply chain professionals to successfully perform each responsibility in a given function. It follows that one knowledge area may have two or more knowledge segments and a group of knowledge areas make the supply chain function complete as one department. To compare and identify the gaps among the three sources, the supply chain function was divided into eight knowledge areas. Further, each knowledge area was subdivided into knowledge segments to comprehend scope details and depth of each knowledge area. The methodology selected for this paper includes a thorough and independent review of the literature published by the abovementioned three sources. After the review was complete, as the first step, the three sources were compared at the knowledge area level. As the second step, the comparison was done at the knowledge segment level. Finally, as the third step of our methodology, a gap analysis was carried out using the literature that was reviewed. The key steps of the methodology are illustrated in Fig. 1.

In the first step, we considered whether the function was fully or partially active, and whether it was benefiting the construction industry, irrespective of the level of its depth and/or maturity. The second step compares maturity level and depth by each knowledge area, in terms of the number of knowledge segments, as an indicator of the tapped areas, irrespective of implementation level at different organizations in the industry. In the entire comparison and analysis process, CII and independent construction researchers were put on the same scale as the abovementioned professional bodies, and an overall comprehensive evaluation was performed of the supply chain knowledge areas (eight in total) and knowledge segments levels in order to present true gaps by benchmarking the world-class practices advocated by the professional bodies. The comparison at the knowledge segment level will help the construction industry identify improvement opportunities, and plan to either adopt those best practices that are missing from their approach or conduct further research on the best ways to customize the best practices to fit the construction industry context and to obtain the maximum possible benefit by elevating the industry supply chain standards.

3 Literature Review

3.1 Professional Bodies Best Practices

This section outlines each of the eight knowledge areas and further discusses each knowledge segment as per the world-class practices identified by the professional bodies. Since the scope and depth of the knowledge areas covered by these professional bodies consider supply chain management an all-inclusive profession, we have considered these practices and research as the benchmark against which construction industry practices can be compared and this comparison shall be the basis of the recommendations, included in Sect. 5 of the present study, for further research to elevate industry supply chain standards.

3.1.1 Warehousing and Inventory Management

Best-in-class organizations have the objective of reducing inventory levels and carrying costs, and improving customer satisfaction by ensuring materials availability. Inventory turnover ratio is an excellent measure of inventory health: the higher the number, better the inventory health and utilization of financials. To determine supply chain priorities from the standpoint of planning, forecasting, controlling and replenishing, the collaborative planning, forecasting and replenishment (CPFR) approach and the Pareto principle (80/20 rule) can be applied to categorize materials into A, B, and C groupings, where category A is the top 20% of items responsible for 80% of the inventory's monetary value. All warehouse activities, including regular cycle and annual full physical counts, must be documented and implemented in full [3]. Introducing vendor-managed inventory (VMI) models greatly help reduce inventory costs [7]. The most popular investment recovery (IR) options include auctions; however, all efforts must be done to avoid root causes of surplus materials [8].

3.1.2 Purchase, Procurement and Contracts Management

Reactive and tactical buying are recommended to be replaced with strategic buying, wherever and whenever possible [9]. World-class procurement attributes include total cost focus, global sourcing, long-term contracts, strategic alliance, company-wide strategic sourcing leverage, world class suppliers, cross-functional teams, and effectiveness measures. Global sourcing requires supply professionals to have knowledge of international marketplace, trade agreements, incoterms, applicable taxes, associated risks, hazardous material handling regulations, and involved costs to perform landed costs and total cost of ownership (TCO) analysis. Further, global sourcing requires having disaster recovery and business continuity plans, and business downturn provisions as part of contract agreements [7]. Consortiums are a recommended way of procurement when the buying organization's purchasing power is low and cost savings is an objective; however, anti-trust and non- disclosure issues must be addressed before entering into any consortiums [15]. Use of producer price indexes (PPI) and proven hedging techniques help reduce price volatility and better manage cash flow. Before the acquisition of capital assets, buy vs lease, internal rate of return (IRR), payback period, net present value (NPV) and life-cycle value analysis must be performed [7]. Services are intangible in nature and this requires documenting a comprehensive statement of work (SOW) when inviting quotes or proposals. Non-professional services procurement can follow the traditional request for proposal (RFP) procurement process [7]. However, qualifications-based selection (QBS) procurement is the method of choice when procuring professional and creative services [14, 17].

3.1.3 Logistics Management

Logistics and transportation are together considered one of the largest supply chain costs to an organization and are a key driver of material and equipment TCO. The eight key principles of LaLonde and Baymond [20] are an excellent guide toward strategic and tactical logistics management. A comprehensive understanding of complex multi-modal transportation is required to move domestic and international shipments; however, international shipments require professionals to fully understand Incoterms, foreign customs and carrier regulations, and the role of freight forwarders (FF) to ensure smooth movement of processed shipments. Logistics and distribution networks must be customized to each project and operations location, as each country and location has unique constraints. Logistics information systems and well-designed comprehensive logistics standard operating procedures (SOPs) are mandatory for efficient logistics. Economies of scale in logistics help generate cost savings and support the organization's financial objectives [7].

3.1.4 Supply Risk and Compliance Management

When dealing with a variety of domestic and international material and service suppliers, supply chains are exposed to multiple low-to-high probability and impact risks. Supply chain departments are today expected to implement a comprehensive supply chain risk management program that must include phases, namely identify risks, analyze risks, prepare risks responses, and monitor risks, after the risk categories are defined and the assessment matrices are in place [3].

3.1.5 Strategic Sourcing Management

World-class organizations deploy dedicated cost reduction teams who systematically follow the "Five-Step Best Practices Framework for Supply Chain Cost Reduction". The five steps are (1) organization and support; (2) know your supply chain; (3) select targets and build the business case; (4) implement the improvements; and (5) evaluate and improve. Proven sourcing cost savings strategies include competitive bidding, strategic sourcing, global sourcing, volume leveraging, reverse auctions, effective negotiations, and supplier integration. The best-in-class organizations link their supply chain to overall organizational objectives and strategies through the "supply segmentation" process, which is the result of corporate spending analysis. The typical supply segmentation matrix comprises the tactical, leverage, critical, and strategic quadrants. Supply professionals develop sourcing strategies and the goals for each quadrant as per business needs and market conditions. The seven-steps of strategic sourcing (i.e., conduct internal assessment, conduct supplier market assessment, collect supplier information, develop sourcing category, solicit and evaluate bids, negotiate and select suppliers, implement recommendations) can be applied to any of the spend categories. Electronic-reverse auctions (e-RAs) help reduce TCO by 10–20% on commodities and services acquisition robust supplier relationship management (SRM) strategies and programs are needed to address all the matters associated with contractors and suppliers [7].

3.1.6 Business Intelligence and Information Technology

Integrated and well-designed enterprise resource planning (ERP) systems provide end-to-end supply chain visibility and facilitate making informed decisions to achieve the set objectives. A deployed ERP system should have all the required modules and must be capable of connecting all organizational departments. Advanced and modern ERP systems may include advanced planning and scheduling (APS), customer relationship management (CRM) and supplier relationship management (SRM) modules. Use of a warehouse management system (WMS) is recommended to satisfy central and large warehousing needs. Barcodes and radio frequency identification (RFID) tags increase control and visibility of costly items [3]. Data mining techniques are in use to understand the buying and usage trends to efficiently plan and forecast the future needs and eventually identify the cost savings opportunities. Valuable supply chain tools including e-RAs, e-Procurement e-Contracts, and purchase cards (P-Cards), etc. are improving overall performance and helping achieve required cost savings, productivity, and visibility goals across the chain [7].

3.1.7 Performance Evaluation and Assessment

Supply chain performance should be benchmarked to applicable world-class practices to elevate overall standards and level of maturity. Effective data collection, a precise and realistic supply performance assessment, and reporting system need to be in place to evaluate and rank its functional, strategic, financial and operational performance compared to the benchmarked standards [7]. Depending on the size of the organization and operations/projects, performance measurement categories may include orders, price/cost competitiveness, supply chain revenue/finance/cash flow improvements, inventory, availability, logistics, technology, quality, workforce, suppliers/contractors, compliance, customer satisfaction, and team performance and development. The use of a balanced scorecard performance measurement system is an advanced approach to align the department activities to the vision and strategy of the overall organization [6].

3.1.8 Supply Chain Teams and Leadership

To become a world-class supply chain manager today, the required skills in addition to the core functional skills include communication management, project management, risk management, decision-making, change management, negotiations, team leadership, and advanced computer literacy. The Supply organizations with Leadership, Strategic vision, Effective and dedicated teams, Cross-functional integration, Development of human capital, Stakeholders management, and Application of functional metrics traits consistently perform best [7].

3.2 CII Best Practices

Integrated ERP with all necessary modules can save a minimum of 6% in terms of labor time cost, result in a 6–12% improvement in labor productivity, approximately 20 and 10% of workers' time can be saved by avoiding material hunting and tracking activities, respectively, and an approximately 7–9% reduction can be realized in terms of surplus material at end of the projects. The major benefits include status reports and end-to-end visibility across materials management [10]. Nationwide logistics agreement with preferred service providers is a major source of cost savings. Project surplus material can be minimized by improving material takeoffs (MTOs), improving planning, effectively communicating changes, and finally by avoiding duplicate purchases. A suitably trained and motivated materials management team with a fully functional ERP system on a project helps achieve optimum results in terms of project cost savings and improved schedule [12]. CII introduced the breakthrough project delivery approach "PEpC" for modern and advanced procurement for the construction industry by splitting the procurement role "P" in the classical engineering-procurement-construction (EPC) delivery method into two stages: (1) strategic procurement of critical and complex engineered components, i.e., the "big P" that drives project schedules should be performed before detailed engineering "E" and the balance of the non-strategic components, materials; and (2) services procurement, or "little p", can be done following the traditional procurement practices after detailed engineering "E" of the project. Results of the advanced simulation models of traditional EPC and advanced PEpC, in both theoretical and field implementations, proved that PEpC has the potential to produce a minimum 10% project time reduction, and a reduction of 4–8% of the EPC costs [13] Sourcing agreements and performance measurements are practiced at 76% of construction organizations, while 63% of organizations maintained strategic supplier relationships at the corporate level. About 50% of the organizations expressed serious concerns over strategic supplier relationships due to confidentiality of their proprietary information; however, the other half showed a desire for standardization of material and equipment, purchase automation, more collaboration, alliances, and early supplier involvement for better overall results. Recently, low-cost country (LCC) sourcing has garnered attention in the industry; however, the sourcing method is sometimes not cost-effective [11].

3.3 Independent Construction Research

Project sponsors are continuously looking for contractors who can make successful project deliveries at the most competitive prices. Cost savings approaches through efficient designs and composite materials during the design stage has been a recent trend; however, the cost savings opportunities through efficient materials management practices are normally not paid much attention [19]. Roughly 50–60% of the total cost of a project lies in materials and equipment requirements, which means improvements in materials management has received the most attention from industry in the last 15 years as total project cost trends have increased significantly [5]. Thomas et al. [25], Al-Khalil et al. [2], and Bell and George [4] have investigated the relationship between labor productivity and ERP systems. The study discovered that the lack of an effective ERP system results in work-hour overruns of 18%. A basic ERP system improves labor productivity up to 6% and a better system can add another 4–6% to this, and it can reduce up to 50% the number of personnel required to manage material on a project site, and can produce 30% material receiving time savings [2, 4, 25]. London and Russell [21] examined industrial practices and the possible ways of implementing the same under the four major supply chain segments (distribution, production, strategic procurement management, and industrial organization economics) with an aim to improve field productivity. The concept of establishing alliances, supplier development, and strategic relationships is new to the industry. It is recommended to develop materials management approaches at the corporate level instead of in the context of a single project [21]. Ibn-Homaid and Naief [16] advised that due to the many similarities between the two industries, the manufacturing industry could assist the construction industry with formalizing and standardizing the materials planning processes, techniques, and approaches for effective projects and overall materials management. Vrijhoef [27] and Meng et al. [22] have presented the SCM maturity model (SCM3) to identify the as-is state of the construction supply chain and to help organizations perceive and plan to achieve a "to-be position" (the next level in the model) per their organizational strategic vision. Vrijhoef [27] believes cost savings of 10–17% are possible when logistics operations are improved, and more cost savings can be realized by involving suppliers and contractors early on projects to identify strategic and partnering opportunities [22, 27]. Ruparathna and Kasun [23] focused on the various type of contracts used by procurement in the construction industry by highlighting the level of risk the parties are exposed to for each contract type.

4 Analysis of the Professional Bodies' Practices, CII Best Practices, and Independent Research

In this section of the present study, we will compare CII best practices and the independent research to the professional bodies' best practices with the aim of determining the potential improvement areas in the industry. One of the factors that need to be considered is that the supply chain knowledge, tools, techniques, and the advocated best practices developed by the professional bodies are not specific to any single industry. Rather, they can be applied to any industry with some customization to best fit the given environment. It is quite probable that the CII might not have considered some knowledge segments, which are not recognized as a good fit for the industry.

4.1 Comparison of the Knowledge Areas

From a broader perspective, supply chain teams at most organizations engage and perform the tasks in all eight knowledge areas as exhibited in Fig. 2. However, the range of application of each knowledge area is different and depends on the number of knowledge segments put in action by supply chain leadership to demonstrate the level of maturity and commitment of the organization. Hence, at the highest knowledge area level, there are no gaps, as all functions are fully or partially active. It may be

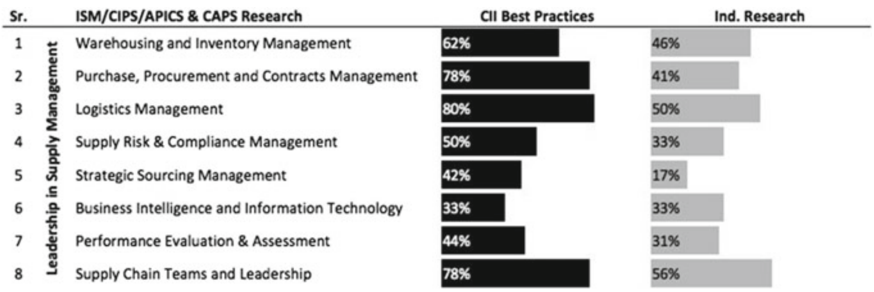

Fig. 2 Comparison of knowledge areas (professional bodies' benchmark)

noted that the names of the functions might differ slightly from one organization or industry to another.

4.2 Comparison of Knowledge Segments

As a second step in the gap analysis, each knowledge area was compared at the knowledge segment level. A summary of this comparison is present in Table 1 along with the details.

1. ***Warehousing and Inventory Management***

Out of a total of 13 consolidated knowledge segments, as shown in Table 2, CII covered eight and independent research covered six segments. Inventory planning, forecasting, control, and standard operating procedures (SOPs) were common across the board.

2. ***Purchasing, Procurement, and Contract Management***

Out of a total of 27 knowledge segments, CII and independent researchers covered 21 and 11 segments, respectively. Procurement, reactive/tactical buying, solicitation, negotiations, contracting, outsourcing, early supplier involvement, global sourcing, supplier performance evaluation, supplier selection process, capital expense procurement, procurement savings, and supplier quality management segments were found to be common across the board.

Table 1 Knowledge areas and count of associated knowledge segments

Sr. Knowledge areas	Knowledge segments		
	ISM/CAPS/CIPS/APICS	CII	Ind. research
1 Warehousing and inventory management	13	8	6
2 Purchase, procurement and contracts management	27	21	11
3 Logistics management	10	8	5
4 Supply risk and compliance management	6	3	2
5 Strategic sourcing management	12	5	2
6 Business intelligence and information technology	12	4	4
7 Performance evaluation and assessment	32	14	10
8 Supply chain teams and leadership	9	6	5
Total	121	69	45

Table 2 Knowledge segments under knowledge area 1 (warehousing and inventory management)

Sr.	ISM/CIPS/APICS and CAPS research	CII best practices	Ind. research
1.1	Vendor-managed/consignment inventory program		Y
1.2	Demand forecasting and inventory planning	Y	Y
1.3	Integrated inventory management system	Y	Y
1.4	Inventory optimization approaches and techniques		
1.5	Inventory carrying cost (ICC) considerations		
1.6	Non-stock inventory management	Y	
1.7	Inventory control and management process	Y	Y
1.8	Pareto analysis for segmentation, control and replenishment		
1.9	Collaborative planning, forecasting, and replenishment (CPFR)	Y	Y
1.10	Disposition and investment recovery best practices	Y	
1.11	Hazardous and/or regulated materials storage and handling	Y	
1.12	Strategies to reduce obsolescence		
1.13	Warehousing standard operating procedure (SOP)	Y	Y
	Knowledge segments counts	8	6

3. ***Logistics Management***

In total, 10 knowledge segments were identified; CII covered eight of them, whereas the independent construction researchers covered five. The knowledge segments distribution networks; overages, shortages, and damages (OS&Ds), incoterms and hazard material regulations; freight, tariffs, insurance; and tracking and status reporting were common across the board.

4. ***Supply Risk and Compliance Management***

CII covered three, and independent researchers covered two out of a total of six knowledge segments. Risk strategies per contract, applicable law, and organizational policies; supplier financial; use of various bonds as risk mitigation strategies were equally addressed.

5. ***Strategic Sourcing Management***

Out of a total of 12 key knowledge segments, CII covered five and independent researchers addressed only two areas. Only the low-cost country sourcing knowledge area was common across the board.

6. ***Business Intelligence and Information Technology***

Of a total of 12 knowledge segments in use, CII and independent researchers covered four each. RFIDs, ERP, and logistics software segments were common.

7. ***Performance Evaluation and Assessment***

The knowledge area associated with performance metrics has a minimum of 32 knowledge segments as per the professional bodies. However, CII has marked 14 and only 10 were found in various independent research papers. Surplus materials, purchase order (PO) cycle, on-time delivery performance, and OS&Ds were found common across the board.

8. ***Supply Chain Teams and Leadership***

Including leadership, 9 professional supply chain teams exist in world-class organizations; CII and the independent researchers recognized 6 and 5, respectively. Inventory, purchasing/procurement, logistics, expediting, and contracts teams were common across the board.

4.3 Gaps and Improvement Opportunities

The gaps identified in each knowledge area with respect to the number of knowledge segments are discussed below and shown graphically in Fig. 3.

1. ***Warehousing and Inventory Management***

The following knowledge segments were found to be missing from the construction industry supply chain literature: vendor-managed/consignment inventory programs, inventory optimization techniques, inventory carrying costs (ICC) considerations, inventory classification for better control and replenishment, and strategies to reduce obsolescence.

2. ***Purchasing, Procurement, and Contract Management***

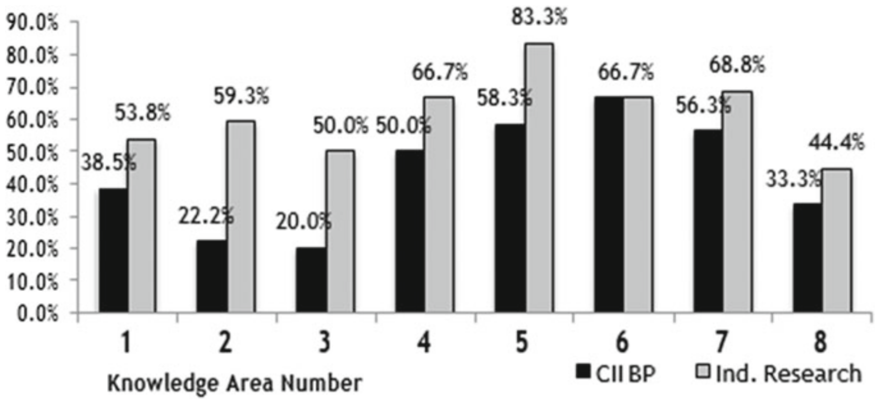

Fig. 3 Percent gaps by supply chain knowledge area

The following knowledge segments were found to be missing from the construction industry supply chain literature: purchasing automation, total cost of ownership (TCO), economies of scale, supplier diversity programs, supplier certification programs, proactive supplier development, supply consortiums, and qualification-based selection (QBS) of professional consultants.

3. ***Logistics Management***

Economies of scale in transportation, and the LaLonde and Baymond [20] principles were not included in the logistics strategies employed in the construction industry.

4. ***Supply Risk and Compliance Management***

Robust supply chain risk management process, free trade agreements, and value chain risk management were found to be the missing knowledge segments in this knowledge area.

5. ***Strategic Sourcing Management***

Strategic sourcing concepts including opportunity assessment, segmentation/category management, market analysis, electronic-reverse auctions, supplier diversity, supplier certification, and supplier exit programs were found to be the missing knowledge segments in the construction industry.

6. ***Business Intelligence and Information Technology***

The following knowledge segments were not found to be part of the construction industry literature and best-practices: business intelligence, data mining, spend analytics, e-sourcing, electronic-reverse auctions, automated e-procurement, self-service e-purchasing, e-contracts management, purchase cards (P-Cards), automation and digitization of procure-to-pay (P2P) process, warehouse management systems (WMS), and block chain.

7. ***Performance Evaluation and Assessment***

The missing knowledge segments that can improve visibility when implemented include the following: suppliers cost competitiveness, cost of non-delivery, percentage of project schedule compliant deliveries, order fill rate, inventory turnover, inventory $s and percentage by class/segment, days on hand stock ($), percentage orders at or below approved budget, e-sourcing and e-procurement trends, freight bill audits, supply chain employees as percent of company employees, average training spend per supply chain employee, and balanced scorecard are.

8. ***Supply Chain Teams and Leadership***

The following knowledge segments do not exist in the construction industry best-practices literature: strategic sourcing/commodity management, business intelligence, and data analytics, and process improvement and standardization supply team.

5 Conclusion and Recommendations

A systematic comparison of three sources of information at the knowledge segment level, i.e., the approaches employed by the professional bodies, the CII best practices, and the work of independent construction researchers, has identified the areas of improvement and led to the discovery that there are ample opportunities for the construction industry to broaden the scope of the field of supply chain management and work towards the next level of maturity. The identified gaps need attention sooner or later as all the identified knowledge segments do not have the same level of urgency for the construction industry in particular, as some of the knowledge segments may also not be applicable in the case of small organizations. However, strategic sourcing, reverse auctions, and vendor-managed inventories (VMI) are the most urgent knowledge segments that require further investigation on a priority basis as they possess the most potential to effectively address the serious concerns of eroding profit margins and increasing construction costs by generating significant (10–25%) cost savings as reported by Accenture [1]. QBS procurement is another key area with the potential to significantly improve the concerns associated with professional consulting services and, ultimately, to improve project performance, quality, and life-cycle cost, specifically public projects where tax dollars are the source of funding. The present study lays the foundation for the industry and construction researchers to set the direction of new supply chain and materials management research and to implement the best-in-class approaches to elevate overall construction supply chain standards. Construction organizations can also benefit from the findings of the present study by evaluating their as-is state and defining the to-be state considering the benchmarked world-class supply chain practices.

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Applying ISO 19650 Guidelines on Digital Deliverables Intended for BIM-Centric Facility Management (FM) in Quebec's Context

M. Robitaille, E. Poirier, and A. Motamedi

1 Introduction

Information takes many forms. Digital models, documents and data are used to create the digital representation of the physical asset [30]. This information should be requested by the owner to serve organisational needs. Asset information requirements (AIR), aligned with the organisational information requirements (OIR) serve the purpose of managing the physical assets of the organisation in an efficient way [18]. This makes the OIR owner-centric and AIR asset-centric. The project information requirements (PIR) on the other hand, serves the purpose of gaining sufficient information for construction professionals to deliver the physical asset. This makes the PIR construction centric. Once formulated and explicitly stated, stakeholders involved in information delivery need to stay aware of the owner's needs and information requirements throughout the design and construction phases to make the digital representation of the asset useful for the owner. Stakeholders must also identify and develop their own information requirements to be useful for their own purposes during the project delivery phase. Managing information in a BIM-centric project consists of responding to these information requirements though a collaborative work process that aligns strategic priorities with efficient communication, effective technological infrastructures and a seamless work process [22]. In other words, the work process focussed on information sharing is as vital to BIM than the

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model itself [28]. Failing to apply this process throughout the lifecycle of the asset is the problem at hand.

As the need to share information applies to all stakeholders, it is desirable to adopt a standardized process that will serve as a common framework to everyone involved in the project [7]. In addition to informing individual stakeholders of procedural expectations, standards help organize and guide entire industries into more coherent and productive ecosystems [33]. ISO 19650 is designed to help raise the construction industry's productivity by optimising the information flow throughout the work process. Work dynamics and relations between stakeholders of any given industry are however influenced by the contract, local context, and industrial specificities. That is why BIM implementation is likely to run into technological, economical, procedural, organisational and legal challenges that originate from internal and external sources, such as local policies [31]. It is hypothesised that the application of ISO 19650 might be influenced by local industrial particularities as well. The research discussed in this paper proposes to analyze how the standard is implemented within the context of the Quebec construction industry. The objective of this research is to identify any potential obstacle that might stand in the way of ISO19650's application. By doing so, it will be possible to suggest solutions for facilitating the alignment of the work process to the standard.

The first step of this research is to perform a literature review covering two subjects of interest: (1) the ISO 19650 standard and (2) the specificities of the construction industry in Quebec. The first will help identify key indicators that express the integration of some ISO 19650 concepts within the work process. The second will identify local particularities of the construction industry and identify external forces that influence the work process. The hypothesis is that stakeholders might not have perfectly integrated the international standard to their work process and that it might be caused by the local characteristics of the industry. This research will then confirm or rebut the hypothesis by performing a case study based on a local project that has been selected as a test drive for BIM integration. Results regarding the production and use of the ISO 19650 key indicators identified in the literature review will inform how the integration of the standard is performed.

2 Literature Review

2.1 ISO 19650 Standard

The objective of the ISO 19650 standard is to frame the organization and digitization of information relating to buildings and civil engineering works. This includes the management of information using BIM [19]. Despite informing about best practices, standards leave it up to stakeholders to adapt the recommendations to their work process [34]. The key concepts addressed by the ISO 19650 standard that need to be integrated within the project's workflow are information requirements (what needs to be delivered), roles and responsibilities (who needs to deliver) and collaborative production (how is the delivery made).

2.1.1 What Needs to Be Delivered?

ISO 19650 makes the distinction between four types of information requirements: organizational information requirements (OIR), asset information requirements (AIR), project information requirements (PIR) and exchange information requirements (EIR). These different requirements are related to each other and depend greatly on the project owner's organizational business strategies [23]. OIR, outlined by the owner, need to align with the objectives of the organization. These objectives are partly pursued through operation of assets. Thus, AIR, determined by asset managers, align with OIR. PIR, specified by the owner, are specific to the construction needs, but some of it might eventually be useful to the contractor. Finally, EIR are necessary to allow the seamless delivery of project and asset information. Without these structured requirements, owners often require as much information as possible, without paying attention to relevance [24]. It is important for owners and asset managers to be actively implicated in project development [2]. The logic behind the information requirement's structure proposed by ISO 19650 reflects that.

2.1.2 Who Needs to Deliver?

The ISO 19650 framework defines stakeholders as being either appointing parties, or appointed parties. An appointed party responds to the requirements of an appointing party. If an appointed party sub-contracts an assignment, he becomes a lead appointed party. Therefore, every lead is responsible for the publication of his delivery team's production [32]. ISO 19650 proposes that stakeholders use responsibility matrices to ensure everyone involved in the project knows who should manage which information. The proposed template, located in the standard's annex, suggests the use of a RACI chart. The RACI chart informs which stakeholders are responsible, accountable, consulted or informed for each given task related to a deliverable [19].

2.1.3 How Will It Be Delivered?

The ISO 19650 standard suggests the creation of a shared digital environment to support information sharing throughout the asset's lifecycle. This digital environment, called common data environment (CDE), helps keeping information secure and accessible to everyone who needs to have access to it. The information found on the shared section of the CDE can also be considered as up to date, making it a trusted reference for every stakeholder [19]. The standard recommends that appointing parties own and manage the CDE, since they will theoretically use the information it contains to maintain and operate the asset. To ensure all relevant information is added to the CDE as the project evolves, the platform should be implemented from the very beginning of the project, even before any appointed party signs a contract. Establishing information management standards is essential for coordinating information integration to the CDE [20]. Efficiently framing information management and the process with which information flows will benefit asset managers by allowing them to keep BIM models up to date. It will, for example, facilitate the integration of data coming from connected objects (IoT) to asset management systems [16]. Since the common data environment (CDE) is a central technological infrastructure that should include every document related to the project, it is an element of interest for studying how the information management standard is implemented in the project. The standard states that the CDE is key to the collaborative process of producing, managing and sharing information [19].

2.2 *Specificities of Quebec's Construction Industry*

It is universally acknowledged that the construction industry is fragmented due to the intrinsically segmented nature of construction projects. Each project phase is usually kept distinct from each other and every phase has a large quantity of stakeholders involved, making the entire process further fragmented [21]. This fragmentation affects the way in which stakeholders communicate and information is shared [26]. It is hypothesised that local characteristics related to professional regulations, geographic and demographic particularities, as well as economic policies might further fragment the construction process and have an influence on the application of new standards related to information management.

2.2.1 Legal Specificities

The Canadian construction industry is highly regulated and professional organisations hold much influence over the stakeholders work process [29]. Quebec is the Canadian province with the most regulated trades [17]. The Quebec construction industry has 25 regulated trades while no other province has more than 11 [8]. The country's political system, built on the union of federated states, decentralises many responsibilities to regional governments, thus creating fragmented legal frameworks that focus on protecting local industrial interests rather than standardizing strategies to benefit the global industry, such as in Japan or in France [29]. The reason behind regulating trades is to control work quality and protect the public. However, a resulting effect of the multiplication of regulations is the reduction of available labor and the reduction of free competition [3, 17]. Regulations also sometimes give labor guilds disproportioned influence over efforts to implement new standards to the work process [4]. The multiplication of trades and heavy regulations contribute to exacerbate the fragmentation of the industry and stand in the way of fluid communication, seamless coordination and harmonious collaboration [26]. A provincial law known as "*Règlement sur l'embauche et la mobilité des salariés dans l'industrie de la construction*" also fragments the industry by regulating the hire of human resources depending on where they reside, reducing therefore the mobility of labor [6]. This law makes it difficult for appointing parties to sub-contract work to qualified businesses that are outside of the project's area [10]. An other specificity of the Quebec construction industry is the "*Loi sur les cités et villes*" [12] and the "*Règlement sur les contrats de travaux de construction des organismes publics*" [13], that makes it mandatory for public contracts to be assigned to the lowest bidder. Yet, anywhere else in north America, the quality of the proposition accounts for up to 90% of the bid's evaluation [9]. Attributing higher importance to the quality of propositions would likely result in more innovative propositions and encourage contractors to explore new ways of working [25]

2.2.2 Geographic Specificities

Quebec is the Canadian province that is aging the most, which results into a decrease of workers dedicated to traditional labor, such as trades involved on construction sites [8]. It is challenging to recruit new workers as older ones leave for retirement. Unfavorable career opportunities, affected by seasonal winter temperatures, make these jobs less desirable [14]. Young workers who chose these trades often end up leaving for other countries, where demand is high, and conditions are more favourable [8]. The devastating effect of harsh winter seasons on the availability of specialized labor is amplified by the geographic and economic isolation [11].

2.2.3 Economical Specificities

The province's economic policies also play a role in the implementation of innovation. Canada's liberal market policy suggests that innovation will happen through businesses seeking opportunities, a process also known as "market pull" [29]. However, the decentralized government occasionally gives provinces the power to bend federal economic policies. Such is the case of decisions related to industrial sectors under provincial jurisdiction, such as the construction industry [27]. Local policies can restrain economic trade with other provinces or certain countries and limit the importation of new professional expertise [15]. Professional competence recognition, financial aid to local businesses, linguistic requirements or local resources quotas are policies that give the province the power to, locally, morph Canada's open market approach towards a policy that can be described as a form of protectionism [3].

As a large public client for infrastructure projects, the government of Quebec also has the possibility to act as a catalyst for innovative improvement. Creating change in an industry through client requirements, also known as "technology push", is common in countries integrating social and economic progress within their national policies, such as France or Germany. Aiming for long term results, these governments use their policies to implement innovative projects that will contribute to social and industrial, long term improvement [29].

3 Case Study

3.1 Description of Project

This research is based on the case study of a project deemed innovative by the way stakeholders agreed to try implementing BIM with the entire lifecycle in mind, meaning that BIM will have to serve the needs of the owner. The project receives financial contributions from the government to push the use of technology and raise the technological maturity of stakeholders. Financial support for technological infrastructure and training is key for BIM implementation since it has been demonstrated that time and money spent on implementing technological equipment and software, as well as the need to train new stakeholders, are the main obstacles keeping businesses from implementing BIM [1]. The delivery of a building information model specifically intended for use in operations and maintenance is the innovative objective of this project and the subject of this study. The project is a new construction which includes 154 residential units, common areas and a chapel, distributed on 4 floors. The bid solicitation was made following a planning phase that included architects, an environmental advocacy group, asset managers, city government and future users. The project delivery system is a design-build method using a CCDC 14 contract [5], implying heighten collaboration between architects, engineers, and contractors. The use of BIM, and the application of standard ISO 19650 is mandated for stakeholders receiving financial support from the government. However, traditional deliverables are still contractually required.

3.2 Methodology

Since the objective of this research is to identify the potential obstacles stakeholders face when trying to apply ISO 19650 recommendations to their work process, a case study approach was chosen to observe and understand how the process unfolds. The complexity of interactions between stakeholders implicated in a collaborative and integrated work process of a BIM centric project makes the case study an appropriate method to gain insight into the dynamics at play.

Selecting a project located in the province of Quebec was relevant since the application of the ISO 19650 standard has not yet been documented in the province. Local specificities of the industry, discussed in Sect. 2.2, will need to be considered during the analysis of results because they might have an influence on the way the standard is applied to the work process, as hypothesised. A mixed methodology approach has been used for studying the application of the information management standard.

A quantitative approach, based on key documents mentioned in ISO 19650, studies how the information is being shared during the work process. The artifacts produced by the project team are analysed and conclusions regarding how the standard was applied is deduced.

A qualitative approach, based on a survey, will help understand challenges faced by stakeholders regarding the application of new standards. The survey was distributed to every individual implicated in the BIM process. Six stakeholders responded to the survey. Among them, three are architects, two are contractors and one is a ventilation subcontractor.

4 Results

4.1 CDE

The CDE of the case study was selected many months after the start of the project and managed by the contractor. This may be interpreted as an indication of how construction-focussed this project might be. In addition to being implemented late and not belonging to the owner, it has been confirmed through interviews that the CDE platform of this project was not exploited to its full potential. As a matter of fact, the coordination, verification, and validation aspect of the work process, done with a web-based coordination tool, has not been integrated to the CDE, as it can be. In the case of this project. The CDE was merely used as a data repository for BIM models and a management tool for change order requests. In parallel to this, another digital platform was implemented in the project at the beginning of the construction phase and used by a few sub-contractors. This tool could be used as an integrated CDE platform to contain, manage, coordinate, and archive all information related to the project, but has only been used for visualising models on mobile devices. This choice of this secondary platform stemmed from a lack of a long-term vision and strategy for the project's information management. The multiplication of software also increase the difficulty for stakeholders to stay up to date with their technological competencies. All respondents to the survey consider the lack of sufficient technical knowledge as one of the top three obstacles to executing their BIM related tasks.

The early implementation of a CDE, as recommended by the standard, could be facilitated by delivery methods aligned on an integrated work process. However, the design-build delivery method used for this project did not seem to contribute to the implementation of a collaborative approach concerning information management. This may have to do with the popularity of the design-bid-build method in Quebec, that has established well rooted habits of fragmented cooperation among industry players, making it difficult for stakeholders to adapt their work habits to a collaborative process. In other words, stakeholders still seem focussed on individual business objectives rather than collective objectives yielding shared profit.

4.2 Information Requirements

As explained in section 1.1.1, ISO 19650 establishes the guidelines for information management throughout the lifecycle of the asset. By doing so, it suggests how information requirements should be formulated. The organisational information requirements (OIR) are the initial requirements that start a chain reaction of requirements that eventually end up creating an asset information model (AIM). The OIR must be formulated by the appointing party (the owner) and must reflect what the organisation needs to function and reach its goals. Without this direct contribution from the appointing party, there is no way to develop quality asset information requirements (AIR) or project information requirements (PIR) aligned with the appointing party's needs.

The appointing party for the case study initially failed to produce an OIR and PIR, which compromised the production of a relevant AIR and EIR. Third parties and consultants had to step in to help identify critical systems and information needs, but the appointing party did not seem to be sufficiently implicated to clearly define a strategy for data use during the operation phase. The platforms and systems to be used for operations and maintenance are still unknown five months in the construction phase. Without a clear strategy for operating the facility management system, it is not clear how the information to be delivered will align with the operation and management needs. Since it is not known how the information will be used by the appointing party, certain aspects of the requirements, such as what level of information granulometry should be delivered for each system, remain unclear. One sub-contractor mentioned that the quantity of information requested seemed unnecessarily high, emphasising the need to make the reasons behind information needs understood.

It has been observed that appointed parties do not always have the technical competencies for supplying the information required by their appointing counterparts. The result of this is, as required by ISO 19650, the transfer of many delivery tasks to the stakeholders who hold sufficient knowledge to do so. The BIM maturity of stakeholders within this project is however noticeably unbalanced. Many responsibilities relating to information management falls on the shoulders of few experienced stakeholders. Four stakeholders of this project reported having to work on tasks that they did not initially plan on executing.

These issues, regarding the capacity to formulate requirements or to efficiently produce information, are related to the industry's BIM maturity. Stakeholders need to integrate information managers within their ranks, to increase their BIM competencies. Appointing parties also need to increase their involvement in projects to take more responsibilities when it comes to defining information needs related to asset management. Having to involve stakeholders as early as possible implicates the need to truly apply the principles of collaborative delivery to the work process.

4.3 Responsibility Matrix

The ISO 19650 standard has a responsibility matrix template included in the annex. The objective of this matrix is to help stakeholders keep track of the management strategy related to information delivery. Being an important document in the project process, it should be included in the CDE, just as contracts and the BIM management plan should. Unfortunately, none of these responsibility assigning documents are present in the CDE, as it is suggested by ISO 19650. The CDE platform however has a section related to the assignment of responsibilities for specific tasks. It is possible, through this function, to fix responsibilities to certain stakeholders, but it falls short of establishing a complete RACI-type structure of relations between stakeholders. Ineluctably, two stakeholders out of six identify the lack of clear responsibilities and objectives as the leading obstacle to the efficient implementation of a BIM centric work process to the project.

5 Discussion and Conclusion

Many of the failures related to the implementation of the ISO 19650 standard could probably be overcome by highly involved facility owners aware of the strategic importance of information management throughout the asset lifecycle. There is an opportunity for professional consultants, specialised in information management, to become essential resources for facility owners who wish to implement BIM to their management strategy. Training a large cross-section of professionals to the basic theories of information management would help reduce BIM maturity gaps between stakeholders. Developing this knowledge should be a priority for facility owners since many key responsibilities related to the digitisation of the industry rest on their shoulders.

The case study has revealed that key concepts of the ISO 19650 standard are not properly understood. A few tweaks and changes in the planning and work process of the project could help align the information flow between stakeholders with the process promoted in ISO 19650. The early implementation of a CDE, and the strategic use of its features, is arguably the most impactful objective related to the implementation of the standard that could improve information flow. As outlined in the literature review, the CDE is much more than an information repository. It also frames the collaborative work process with tools enabling coordination between stakeholders. The standard allows the use of multiple CDEs. However, it is wise to limit the number of digital tools and platforms to reduce the risk of information loss since it will limit the transfer of data from one environment to another. Establishing a long-term information management strategy would help streamline technological resources and use each application or platform to its full potential. For this to happen, stakeholders should be implicated earlier in the process and the formulation of OIRs, and AIRs should be done before the start of the project. The responsibility matrix, that has been identified as a key indicator of the application of ISO 19650, was not developed for the project in the format provided as a template in annex A of the standard. Since the responsibilities assigned through this matrix are directly related to the application of the standard, it might be part of the solution to ensure it is thoroughly produced and shared among stakeholders.

Until now, stakeholders are asked to adapt their work process to the ISO 19650 standard through a contractual request formulated in general terms. The request formulated in contracts asks for all work to be executed in conformity to the standard. This leaves too much room for interpretation and does not give the appointing party the necessary tools to make any follow-up or verification on the application of the standard. Asking for the delivery of key documents related to the standard could be a way to ensure the right steps are taken to adapt the work process to ISO 19650.

6 Limitations and Future Work

By nature, a case study usually offers little basis for generalization of results. The technological maturity of stakeholders and the level of collaboration between individuals are variables that vary greatly from one project to another. The type and scope of projects are also uniquely configurated parameters that make the replication of the exact same study for validation purposes close to impossible. The information found in the literature review of the local industry however helps contextualise the observed behaviour of stakeholders in this case study and determine if it aligns with local tendencies.

Consequences related to the COVID-19 pandemic may have affected the study. These include teleworking, high turnover rates among stakeholders, and localised outbreaks among stakeholders. The probable effects are implications on the quality of feedback, availability of stakeholders and the collaborative work context of the project.

Future research should focus on including requirements of specific key documents mentioned in ISO 19650 in contractual agreements between appointing and appointed parties in the contracts and analyse the effects on the integration of the standard.

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Assessing the Carbon Cost of Utility Installation via Multi-Utility Tunnels (MUTs)

A. Hojjati, D. V. L. Hunt, and C. D. F. Rogers

1 Introduction

Global population growth, increasing urbanisation, sprawl and the emergence of new cities and towns are fuelling need for far more buried utility infrastructure. Although there are alternatives to traditional open-cut methods of utility installation, their short- and long-term cost estimation(s) are lacking. Many authors state that they should not be limited to economic costs, but broadened to include social and environmental impacts [13–17, 19]. In contrast to economic and social costs, carbon emissions for utility works have been under-reported, primarily because they are relevant to long-term, whole-life considerations [17], yet carbon costing is increasingly viewed as justification for changes to construction practices to account for environmental consequences of works. This research aims to justify the use of Multi-Utility Tunnels (MUTs) for utility installation as an aid to sustainable development. This is achieved by comparing the short-term (MUT construction) and long-term (i.e. maintenance, upgrading, renewal) carbon costs for utility installation via traditional open-cut methods and a newly-constructed MUT. Building on the work of Hunt et al. [17], the carbon cost comparisons were determined for undeveloped (greenfield) and urban (high density) locations, i.e. the carbon embodied within the MUT's structure and that due to the construction process, and where the tipping point occurs such that MUTs become a preferred option in terms of carbon saved.

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2 MUTs and Carbon Accounting

MUTs can accommodate many types of utility (water, wastewater, gas, electricity, telecommunications) and represent a 'smart' and 'open-ended' approach [19]. They can be constructed as flush-fitting shallow (visible), (searchable) conduits, and deep (compartmentalized) tunnels, and offer significant advantages over traditional installation methods in terms of: assured utility placement, leak detection, ease-of-access for maintenance, replacement and utilities upgrading. However, the short-term economic costs are likely to be significantly greater [17] and there are other barriers to their adoption. Table 1 lists advantages, barriers, and possible enablers to the implementation of MUTs, showing the strongest enablers being related to locations where the utility infrastructure is independently owned and operated.

One of the most important considerations in today's construction industry is the issue of carbon accounting; this will form an essential part of the environmental costing of MUTs. It is therefore essential to calculate and compare the carbon embodied within an MUT with that associated with traditional utility installation, maintenance, and refurbishment. According to UK Government policies, crafted to meet the Kyoto Protocol of 1997 objective of reducing CO_2 emissions by at least 80% by 2050 from a 1990 baseline [8], the construction industry was identified as a major contributor to the carbon emissions: it requires huge quantities of materials to be extracted, processed and transported to site, while 'operational carbon' includes emissions arising from the use and maintenance of vehicles, machines and ancillaries such as lighting and cooling equipment. Additionally, emissions like CO_2 may be 'embodied' within materials: in the Inventory of Carbon and Energy (ICE, [11]) "*Embodied energy (carbon) is defined as the total primary energy consumed (carbon released) from direct and indirect processes associated with a product or service and within the boundaries of cradle-to-gate. This includes all activities from material extraction (quarrying/mining), manufacturing, transportation and right through to fabrication processes until the product is ready to leave the final factory gate.*"

Table 1 Advantages, barriers, and possible enablers of Implementation of MUTs (after [16])

Advantages	Barriers	Enablers
Long-term financial benefits (such as ease of maintenance, upgrading, leakage detection)	High short-term capital cost	Site owners (e.g. universities, hospitals) are able to exploit long-term benefits
Long service life of MUTs	Lack of long-term planning for utility installation	Increased flexibility for future utility installation/upgrade
Assured utility placement/avoidance of damage	Lack of funding and bodies willing to own/operate	Sustainable (social, economic, environmental) costing models
Ease of location	Poor company coordination	Change governance policies
Minimal surface disruptions at the time of maintenance	Lack of practical experience, knowledge, and case studies	Increased awareness of whole system benefits

Carbon calculation methods and databases of the amount of embodied carbon of construction materials are available for different types of projects and should be considered for the carbon calculation of MUTs. However, although there are many tools and calculators for the carbon footprints in the construction industry, not all are likely to be widely applicable for construction works. This is because of the differences in energy generation methods, combined with material production and transportation procedures, in different countries, leading to different patterns of carbon emissions [18]. In addition, several countries have no publicly available databases of carbon emissions and impacts of construction materials and activities [2]. Helpfully, in the UK, the Carbon Trust [6] and the Inventory of Carbon and Energy (ICE) have published updated databases, while the Swiss database Ecoinvent [20] is used in Switzerland, Germany and the Netherlands, the Athena Institute [3] database is available in Canada and in the USA, there is the US Life Cycle Inventory [21]. Moreover, different industry sectors have developed their own assessment tools appropriate to their needs, for example, in the UK, the Environment Agency [9] and the National House Building Council have developed their own tools based on the UK Carbon Trust and the Inventory of Carbon and Energy (ICE) databases. Bespoke tools for the utilities and trenchless technology industries could, therefore, be created.

2.1 Inventory of Carbon and Energy (ICE)

The University of Bath's Inventory of Carbon and Energy was developed as an open-access and reliable database of both embodied energy and carbon for construction materials, particularly in the UK construction industry [12]. It lists data for almost 200 construction materials extracted from reliable literature sources: peer-reviewed journal papers, technical reports and monographs based on a precise methodology, for example, Chartered Institution of Building Services Engineers [7] and Boustead and Hancock's handbook [4]. All of the literature drawn on for the ICE was consistent with Life Cycle Assessment (LCA), as recommended by the International Organisation for Standardisation (ISO). A particular feature of the ICE model is that it incorporates a simple sub-model that estimates the embodied energy and carbon for cements, mortars, and concretes according to their constitutions, thus enabling the ICE to be more flexible and accurate when using the database for real world case studies.

2.2 Environment Agency (EA) Carbon Calculator Tool

This online Carbon Calculator Tool (CCT) was created in an Excel spreadsheet format by the Environment Agency (EA) in collaboration with Jacobs Consultants. It measures the environmental impact of construction materials by calculating the embodied CO_2 of construction materials and the amount of CO_2 emitted due to their transportation, using calculations and databases taken from the ICE. The tool offers the opportunity to reveal carbon savings strategies in the planning and design stages of a project and estimate the overall carbon footprint of a finished project. The spreadsheet allows the user to enter the quantities of material used in the project, the transport distance and mode of transport (rail, road, and water). For some materials it is possible to enter more detail (e.g. the type of cement and percentage of aggregates used in a concrete mix), while the project size is used to estimate the emissions from staff personal travel. The EA tool essentially multiplies the tonnage of materials (plus unit of distance travelled) by the emissions factor associated with that particular material, to give the CO_2e or 'equivalent carbon footprint' associated with it. While the EA calculator is a generally well accepted, if far from intuitive, approach to carbon accounting, providing comprehensive results for different materials and considering impacts of both construction and other related activities, further investigation regarding its performance and applicability to MUTs is needed. Nevertheless, it can be considered an appropriate tool for benchmarking of MUT's carbon costs. Figure 1 shows an overview of the EA tool. The orange cells representing data that need to be entered into the tool by the user, and green cells indicate data which already exist as the background information of the calculator.

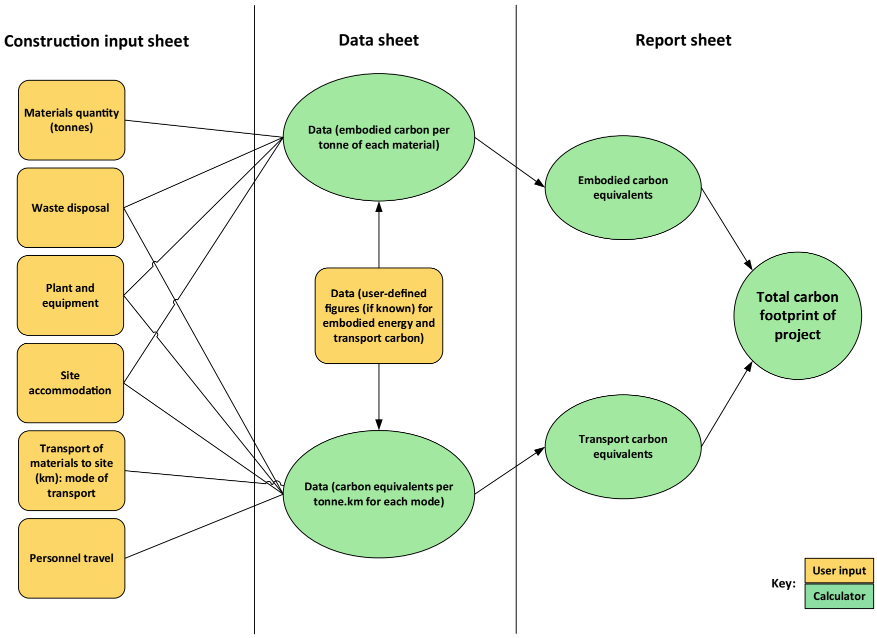

Fig. 1 Overview of the EA CCT (adapted from EA [9])

3 Estimating the Carbon Footprint of Utility Installation Methods

3.1 Methodology

The foundation of this research involved calculation and comparison of carbon emissions due to open-cut methods and flush-fitting MUTs using the EA CCT. A simple model for the utility tunnel was defined to enable material quantities (by weight) to be calculated, along with assumed distances from material supply source to the site and from the site to landfill. The material quantities were input into the CCT, which contains the embodied carbon for all materials considered. The figures presented in the following sections of this paper represent the embodied carbon of materials used in each utility placement method together with the transportation carbon due to material supply and waste taken to the nearest landfill, to provide generic cost comparisons. Carbon footprints of plant and equipment, staff personal travel and staff accommodation in a project were not considered in the calculations; these will be site- and project-specific and should be determined for specific case studies.

Short-term calculations (for the construction stage of utility installation) were carried out for both open-cut method and flush-fitting MUTs. Open-cut construction operations involved excavation, pipe placement and surface reinstatement, while for flush-fitting MUTs they were excavation, culvert placement and utility pipe placement. It was assumed that one 200 mm diameter steel pipe (UK/EU average recycled content) was installed in the open-cut trench and the flush-fitting MUT in order to calculate the basic carbon footprint of material used in two different locations: undeveloped (greenfield) and urban areas. Calculations were then carried out for an increasing number of pipes and Excavation and Reinstatement (E&R) operations in each location to reveal the carbon production trends and to perform a sensitivity analysis of the results.

The long-term carbon costs concerned carbon emissions due to the post-construction works involved in routine maintenance and renewal of utilities. These costs were based on the number of E&R operations typically encountered in the UK for the open-cut method compared to those involved for MUTs.

3.2 Carbon Measurements in Open-Cut Installation

In order to quantify the amount of material in an open-cut utility installation, a 1.0 m × 1.0 m × 1.0 m trench was considered in each location (undeveloped and urban). One 200 mm steel utility pipe is placed at shallow depth via open-cut trench on asphalt-covered road or footway. Soft materials were backfilled according to the location of the placement and any excess soft materials (i.e. volumes equivalent to that of the pipes) sent to landfill. Preparations of all surfaces were assumed based on the location of the work.

Distances for material transportation to and from site, which is an important factor in the CCT calculations, vary for each area. This is because the distance between construction sites and the material supply source or landfill in an urban area was assumed to be greater (25 km) than the distances for an undeveloped, greenfield site (15 km, see WREN [22]). These distances were checked by Google Maps for Birmingham area as an example and found to be representative. Materials were assumed to be locally sourced to have the least environmental impact. The mode of transportation was considered to be by road in all cases.

3.2.1 Undeveloped Areas

A 1.0 m × 1.0 m × 1.0 m trench in soft soil was assumed to be excavated, and subsequently backfilled with the same soft soil, in an undeveloped, or greenfield, location [17]. A total of 1 m^3 of soft soil with a density of 1.7 tonnes/m^3 was excavated (yielding 1.7 tonnes of soil). The weight of a 200 mm steel pipe with outside diameter of 219 mm, inside diameter of 203 mm and a wall thickness of t = 8.2 mm was taken to be 43 kg/m length [10]. The volume occupied by the pipe was calculated to be 0.038 m^3, meaning soft soil equal to this volume and weighing 0.065 tonnes was transported to landfill and 0.962 m^3 of soil weighing 1.635 tonnes was backfilled in the trench (Table 2).

Using inward and outward transportation distances by road of 15 km, the carbon footprint figures for each material have been calculated by the CCT according to their respective weights in Table 2, yielding 0.102 tonnes, or 102 kg, of CO_2 per metre length of utility installed—the carbon footprint for open-cut installation.

Table 2 Material quantities and associated carbon footprints (per metre length of installation, using the CCT) of an open-cut utility installation using one 200 mm steel pipe in undeveloped areas

Material	Density (tonnes/m^3)	Volume (m^3)	Weight (tonnes)	Distance (km)	Mode of transport	Carbon (tonnes/m)
Soil (waste to landfill) = volume of one pipe	1.70	0.038	0.065	15	Road	0.001
Soil (backfilled soft soil)	1.70	0.962	1.635	0	–	0.039
Pipe material (steel)	7.80	0.038	0.043	15	Road	0.062
Total carbon footprint						0.102

3.2.2 Urban Areas

The same basic calculations were done for urban areas assuming that a 500 mm (0.5 m) depth of made ground surfaced by bitumen macadam, considered as mixed commercial and industrial waste with a density of 2.4 tonnes/m^3 in the CCT, was removed and sent to landfill [17]. The weight of this 0.5 m^3 (i.e. 0.5 m wide × 1 m deep × 1 m length) of surface material excavated was 1.2 tonnes. The underlying 500 mm of soft soil was excavated and subsequently reinstated as backfill. Surface reinstatement was assumed to be carried out using a 200 mm hardcore sub-base, overlain by a 300 mm dense bitumen base, binder, and surface course [17]. The volume, weight and associated carbon footprints of these layers are shown in Table 3, while the pipe material and dimensions are the same as those used for undeveloped areas. Material transportation distances were assumed to be 25 km for urban locations, based on average historical distances to landfill sites in the UK [5]. This yielded a total carbon footprint of 0.399 tonnes, or 399 kg, of CO_2 per metre length of utility installed.

Comparing the findings for the two locations (undeveloped and urban), it is evident that carbon emissions increase by almost 300% due to the change in material type and quantity (materials removed to landfill and reinstatement materials supplied to site). Interestingly, the difference in material transportation distances was found to have only a small impact on the overall carbon footprint.

Table 3 Material quantities and associated carbon footprints (per metre length of installation, using the CCT) of an open-cut utility installation using one 200 mm steel pipe in urban areas

Material	Density (tonnes/m^3)	Volume (m^3)	Weight (tonnes)	Distance (km)	Mode of transport	Carbon (tonnes/m)
Soil (waste to landfill)	2.40	0.500	1.200	25	Road	0.242
Soil (waste to landfill) = volume of one pipe	1.70	0.038	0.065	25	Road	0.001
Soil (backfilled soft soil)	1.70	0.562	0.955	0	–	0.023
Pipe material (steel)	7.80	0.038	0.043	25	Road	0.062
Hardcore sub-base	2.00	0.200	0.400	25	Road	0.033
Dense Bitumen base course	1.70	0.300	0.510	25	Road	0.038
Total carbon footprint						0.399

3.3 Carbon Measurements in MUTs

Flush-fitting MUTs, consisting of rectangular pre-cast concrete culverts with flush-fitting lids, have been used widely, such as for the 1992 Olympics in Spain and on the University of Birmingham campus (see Hunt et al. [16]). These surface access MUTs typically have external dimensions of 1.0 m × 1.0 m × 1.0 m, and are categorised as Class 1 (pedestrian areas such as footways, walkways and cycle tracks) or Class 2 (low traffic private driveways and grassed areas). The weight of such a culvert (1224 kg) and its flush-fitting lid (262 kg) gives a total of 1486 kg (1.486 tonnes, Aggregate Industries [1]), as shown in Table 4. For this research, flush-fitting MUTs were modelled as a 1.0 m × 1.0 m × 1.0 m precast concrete culvert with a lid flush to the surface in an asphalt-covered road or footway. Excavation for flush-fitting MUTs was assumed to require 45 degree slopes on both sides for stability and to provide working space [17]. The volume of soft soil and made ground taken to landfill was consequently considerably greater than open-cut method, because of the size of excavation required and the size of the flush-fitting conduit being installed. As before, excavated material equal to the size of the flush-fitting conduit were taken to the landfill with transportation distances of 15 km, and 25 km for undeveloped and urban areas, respectively. However, the volumes of slope material (excavated for stability and working space) were backfilled once the culvert was in place. The pipe material and dimensions were the same as for the open-cut construction.

Table 4 Material quantities and associated carbon footprints (per metre length of installation, using the CCT) of a flush-fitting MUT housing one 200 mm steel pipe in undeveloped areas

Material	Density (tonnes/m^3)	Volume (m^3)	Weight (tonnes)	Distance (km)	Mode of transport	Carbon (tonnes/m)
Soil (waste to landfill)	1.70	1.000	1.700	15	Road	0.041
Soil (backfilled soft soil)	1.70	1.000	1.700	0	–	0.037
Pipe material (steel)	7.80	0.038	0.043	15	Road	0.062
Pre-cast concrete culvert with lid	1.35	–	1.486	15	Road	0.161
Total carbon footprint						0.301

3.3.1 Undeveloped Areas

The volume of materials initially excavated for the 1.0 m × 1.0 m × 1.0 m MUT with side slopes of 45 degrees was calculated to be 2 m^3 (3.4 tonnes), with half of this material (1 m^3, 1.7 tonnes, equivalent to the volume of the culvert) removed as waste and transported to landfill and the remaining 1.7 tonnes used to backfill around the MUT. The pre-cast concrete culvert with lid accounts for the largest amount of embodied carbon (0.161 tonnes of CO_2 per metre placed), while that of the pipe material remains the same as for the open-cut installation. Calculations performed using the CCT and presented in Table 4 gave 0.301 tonnes (301 kg) for the total carbon footprint of installing a 1.0 m × 1.0 m × 1.0 m flush-fitting MUT containing one 200 mm steel pipe in an undeveloped area. [It should be noted that the carbon cost of the concrete could be significantly decreased by using replacement materials (e.g. Fly Ash and Ground Granulated Blast Furnace slag) for a proportion of the cement used within the concrete mix (e.g. AlMulhim et al. [2])].

3.3.2 Urban Areas

The equivalent calculation for urban areas, as expected, differs only in terms of material types and quantities. The main difference in terms of material quantities is that the subsurface material in urban areas is not soft soil. In urban areas subsurface material is assumed to be made ground with a greater density (2.40 tonnes/m^3) and consequently weight [9]. The 1 m^3 of waste material which should be sent to landfill has a weight of 2.4 tonnes. With a 45 degree slope to the excavations, this means that 1 m^3 of made ground needs to be excavated and removed to landfill, while 1 m^3 of soft soil is excavated and is used as backfill. Table 5 presents the breakdowns of material types, quantities and their carbon emissions for this case, from where it can be seen that the total carbon cost is 0.750 tonnes (750 kg) per metre length of utility installed: far more than the value obtained for a flush-fitting MUT installed in undeveloped (greenfield) conditions.

4 Evaluation of Results

As discussed above, total carbon footprint figures have been calculated using only one pipe (a 200 mm steel pipe) as the baseline installation requirement. It can be seen from the tables that the contribution towards the overall carbon footprint of materials transportation is substantially less than the embodied carbon of materials themselves, provided that the locations of material supply and landfill for waste deposition is in close proximity (i.e. as in the UK, <25 km). More importantly, it can be seen that the carbon costs of utility placement in the short-term (i.e. immediately after construction) for MUT construction is considerably greater than that of open-cut construction in both undeveloped, or greenfield locations (0.301 versus 0.102 tonnes of CO_2 per

Table 5 Material quantities and associated carbon footprints (per metre length of installation, using the CCT) of a flush-fitting MUT using one 200 mm steel pipe in urban areas

Material	Density (tonnes/m^3)	Volume (m^3)	Weight (tonnes)	Distance (km)	Mode of transport	Carbon (tonnes/m)
Soil (waste to landfill)	2.40	1.000	2.400	25	Road	0.484
Soil (backfilled soft soil)	1.70	1.000	1.700	0	–	0.041
Pipe material (steel)	7.80	0.038	0.043	25	Road	0.062
Pre-cast concrete culvert with lid	1.35	–	1.486	25	Road	0.163
Total carbon footprint						0.750

metre length of pipeline) and urban locations (0.750 versus 0.399 tonnes of CO_2). This is mainly because construction of MUTs requires considerably larger quantities of materials to be excavated then transported from site to landfill and likewise materials transported onto site (i.e. pre-cast concrete culverts, and where necessary reinstatement materials). When considering the short term, therefore, trenching is the less carbon intensive approach to utility placement.

4.1 Sensitivity Analysis

What has been presented so far was the quantification of basic carbon footprints for the installation of a single pipe via traditional open-cut and flush-fitting MUTs. However, for a more realistic assessment (i.e. throughout the lifetime of the utility pipelines) the long-term carbon costs of maintenance and renewal of utility systems should be included and combined with the installation costs of a larger number of utility pipelines since an MUT has considerable capacity. In order to investigate these long-term carbon footprints for the two types of utility installation methods, the costs of E&R procedures for repair, replacement or upgrading have been considered for the open-cut case, these costs not being relevant for MUTs. This has been done on the form of a sensitivity analysis (a study of the influence of the frequency of a parameter on the model's output) based on increasing number of yearly E&Rs in both locations. The number of pipes has been increased from one to 15 for both open-cut installation and flush-fitting MUTs, with the calculations reflecting the initial carbon footprint figures using one 200 mm steel pipe for the open-cut case and simply delivery of the pipe to site for the MUTs. It should be noted that whilst the size and material type for pipes (e.g. polypropylene vs. clay vs. cast iron vs. concrete vs. electrical cables)

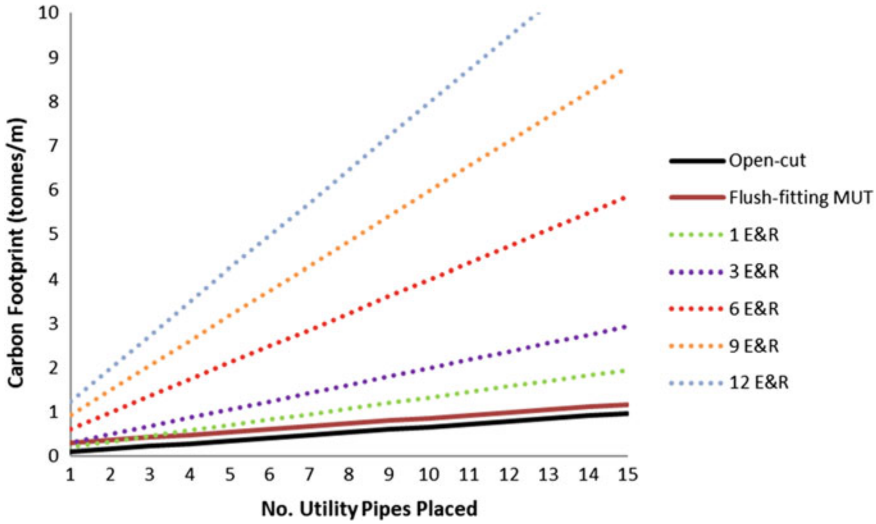

Fig. 2 Carbon costs for flush-fitting MUTs versus open-cut with and without yearly E&Rs (undeveloped areas)

are beyond the scope of this paper, they would have an impact on the resulting calculations.

In order to study the long-term effect of maintenance, renewal and upgrading of utility pipes on the size of their carbon footprints, material and carbon calculations, determined using the CCT, for 1, 3, 6, 9 and 12 yearly E&R procedures have been carried out for undeveloped (Fig. 2), and urban (Fig. 3) areas.

Figure 2 for undeveloped areas shows the lines for a single 200 mm steel pipe installed via open-cut or in an MUT are offset and the two lines do not cross. However, when we add in the carbon costs for repeated yearly E&R required for the routine maintenance, renewal or emergency repairs with respect to open-cut the lines cross and then lie above that for the MUT option, indicating that carbon is being saved due to placement of utility pipes via the MUT option. This saving increases considerably as both the number of utilities placed and number of E&Rs rises, as might be expected. Moreover, Fig. 2 shows that the tipping point(s) in favour of MUTs occur when installing 3 pipes with one E&R operation. After this threshold, the carbon savings are very much in favour of the MUT option: the greater the number of pipes installed and the greater the number of E&Rs, the greater the carbon savings. Thus, streets with high occurrences of both would benefit, in terms of carbon savings, through the adoption of MUTs. This would be in addition to the economic costs that could be saved (see Hunt et al. [17]). The same analysis was conducted using the carbon footprints for urban areas (Fig. 3), with similar general observations, yet the tipping point occurs with only one annual E&R procedure for a single 200 mm steel pipe. Moreover, the savings made as the number of pipes and E&Rs increases is much higher than in undeveloped areas.

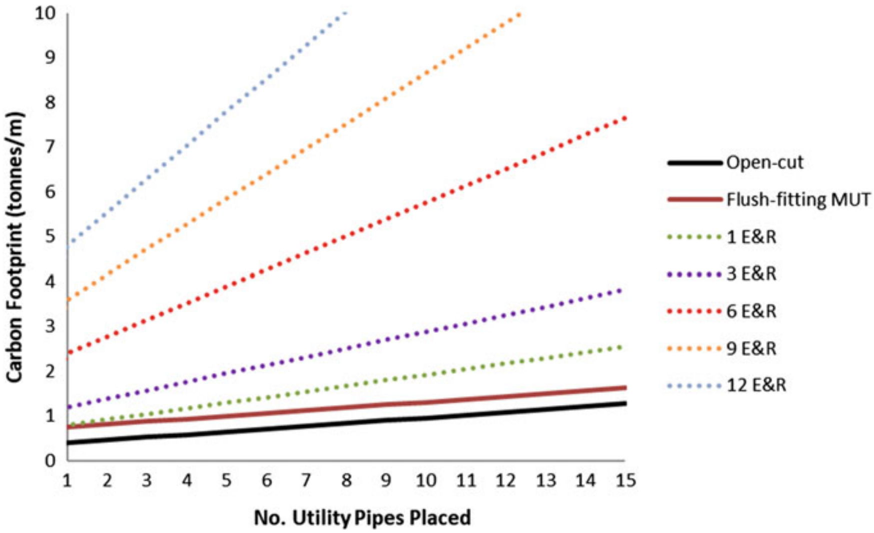

Fig. 3 Carbon costs for flush-fitting MUTs versus open-cut with and without yearly E&Rs (urban areas)

5 Concluding Discussion

The aim of this research was to estimate the carbon costs of utility placement via MUTs compared with those for traditional open-cut excavation methods for different construction contexts: undeveloped (greenfield) and urban areas. Carbon cost comparisons have been presented for each option and location when considering both the short-term (i.e. construction stage) and long-term (i.e. post-construction stage). The data were analysed through a sensitivity analysis with an increasing number of pipes (1–15) and number of E&R procedures (1–12). The results showed that the carbon costs for construction of flush-fitting MUTs are significantly higher than those for open-cut installation in both locations when considering installation of a single 200 mm diameter pipe (i.e. 750 kg carbon per metre length of flush-fitting MUTs compared to 399 kg carbon per metre length of open-cut installation in urban areas).

However, in urban locations this conclusion changed when considering only 1 subsequent E&R operation even with only 1 utility present; for undeveloped areas the carbon savings were in favour of MUTs when the number of utilities increased to 3 with 1 subsequent E&R operation. Beyond these tipping points, the greater the number of pipes installed and/or number of E&R operations occurring the greater the carbon savings that can be made. In other words, a flush-fitting MUT, in the long-term, can be considered to provide an environmentally sustainable solution from a carbon costing point of view for subsurface utility placement, and the case for MUTs becomes most compelling for streets where many pipes need to be installed and/or the occurrences of E&R operations are high. This would be in addition to the significant economic costs that could be saved.

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Adaptations of Municipal Solid Waste Management Systems in Response to the Coronavirus Pandemic

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1 Introduction

Pandemics are massive outbreaks of contagious diseases that not only affect public health but also cause significant social, political, economic, and environmental disruptions while disrupting essential services, such as waste management. According to the Solid Waste Association of North America (SWANA), the changes in waste volume and solid waste source result from the issued work-from-home advisories and stay-at-home ordinances [13]. This pandemic has changed our daily routine activities and has led to the shift of waste production trends. Consequently, regional municipal solid waste management systems (MSWMSs) have been facing various challenges in their operations. For instance, the amount and frequency of online shopping have increased drastically due to local business closures, and thus increasing packaging waste volumes such as used cardboard and plastic. Another reason for these changes in waste volume is the excessive stockpiling behavior due to panic buying of long-life food, toilet papers, disinfectant products, and other essential goods [8]. Likewise, the package of online delivery food and takeout has increased since people are spending more time in their residences and cannot dine-in restaurants. This increase in packaging waste affects the municipal waste facilities' capacities and increases the environment's pollution due to plastics and other non-biodegradable materials [16]. Concerns about the transmission of the disease via surface contact have risen, leading to several states like New York and New Hampshire to suspend their single-use plastic bans temporarily [10]. These changes in policies and fear of transmission via surfaces have caused increased plastic waste and changes in consumers' mindset on recycling. Additionally, people's new habits,

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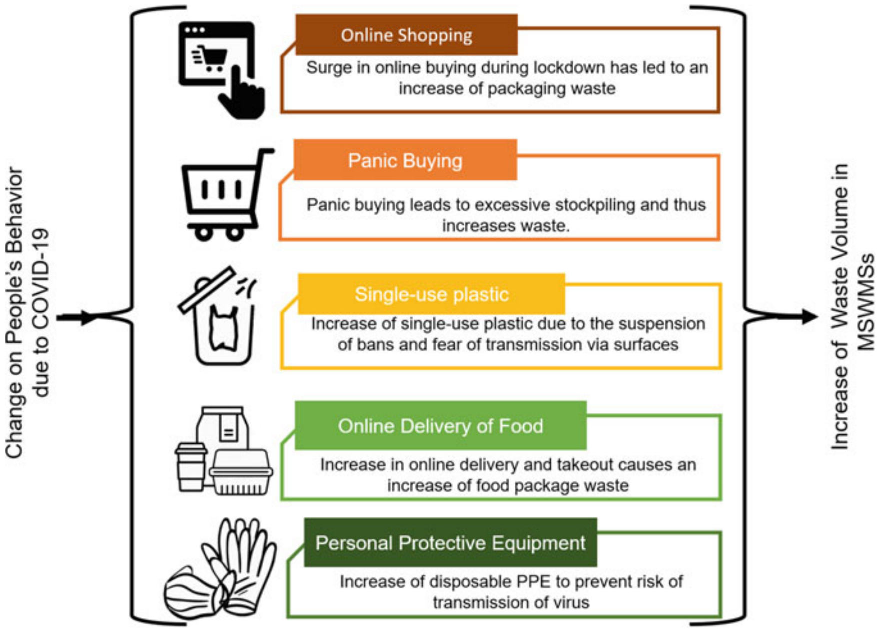

Fig. 1 Impact of the COVID-19 pandemic in people's behavior leads to changes in waste volume

such as the use of disposable personal protective equipment (masks, face shields, and gloves), have increased the volume of plastic waste [16]. Figure 1 shows, in brief, the repercussions of people's behavioral changes due to the COVID-19 pandemic on municipal solid waste management.

As of March 12, 2021, various responses have been implemented to minimize the spread of the COVID-19 coronavirus and minimize its toll in our society, from the closure of business to lockdowns in order to ensure people's safety. Also, in an effort to mitigate its negative impact, many countries have endeavored to maintain indispensable services essential to the population's welfare during this type of disastrous event. One of these essential services is waste management services; this includes waste collection, treatment, and disposal. MSWMSs play a significant role in protecting communities by minimizing waste contamination and limiting the spread of infectious diseases [5, 15]. MSWMSs not only provide waste services that protect the environment but also safeguard the well-being of the people by reducing the hazardous waste exposure. If such critical infrastructure fails, it would incur serious environmental challenges, health problems, and even economic concerns. Despite the importance of waste management as an essential service, most pandemic-related studies have primarily focused on the pandemic's impact on public health systems. This means that there is limited or lacking details on how pandemics have affected individual MSWMS entities (i.e., landfills, waste incineration facilities, materials recovery facilities, waste transfer station, and waste collection) and how these entities have been implementing adaptive measures in response to pandemic-related challenges. Furthermore, the MSWMS operations changes due to the infection concerns and travel bans have restricted MSWMS's ability to receive external support. This has make MSWMSs rely only on their limited resources to provide waste services.

To address this gap, this research uses a three-phase framework to understand and characterize the adaptation processes of MSWMSs with respect to their challenges during the pandemic. Through this framework, we identified a wide range of waste management and operational challenges along with adaptive measures taken by different MSWMSs in the U.S. Please note that this study reports these challenges and adaptive measures in terms of system structure, urban settings, and other regional factors. The next section presents prior studies on resilience assessment of MSWMS in extreme events such as a flood [3], which lead to the gap in the current best management practices to effectively tackle the challenges emerging during the pandemic. This is followed by the proposed three-phase framework. Lastly, we identified challenges and measures taken by MSWMSs made during the pandemic along with a discussion on their different adaption processes.

2 Municipal Solid Waste Management Systems' S Resilience During a Natural Disaster

The operations and design of MSWMSs can be largely affected by natural disasters, such as hurricanes and floods. In preparation for such disruptive events, researchers and government agencies have developed qualitative and quantitative guidelines for regional MSWMSs in advance to guide public agencies on the effective management of the systems [14]. For instance, Beraud et al. [3] used functional analysis to understand the complexity of a theoretical household waste management system and demonstrated its application to guide the preparedness of an existing waste management system for flood events. To ensure that the system remains in operation at an acceptable level of operation even during the disruptive events, this study considered both external (e.g., regulatory authorities) and internal system components [3]. Phonphoton and Pharino [9] employed a system dynamic approach to demonstrate the system connections and changes emerging within waste management operations during flooding situations. To be more specific, this study evaluated a network vulnerability of different MSWMSs (at a district level) to access waste management processes following the disasters. Mamashli and Javadian [7] also demonstrated how the operations of an MSWMS can be adapted in the event of uncertainties characterized by unpredictable extreme events (e.g., in the form of urbanization and changes in waste generation patterns). The authors proposed a municipal solid waste network design to optimize the network efficiency by considering facility locations and the impacts of waste generation on the community. Bavaghar Zaeimi and Abbas Rassafi [2] also proposed a fuzzy chance-constrained optimization model to design the operations of an MSWMS. The authors also claimed that it is important to determine the optimal locations for waste facilities while minimizing the overall system's operational costs in order to remain resilient to urcertain extreme events.

Although some studies have explored issues faced by MSWMSs during natural disasters or other disruptive events, most of these studies are not applicable to the development of strategies for pandemic events since pandemic events differ from natural disasters due to their nature and characteristics. For instance, the primary sources of generated waste during a pandemic are usually affected (e.g., household waste) while in the case of natural disaster, primary sources of waste are due to the impacts on the built environment such as buildings and other civil structures. Also, unlike in natural disasters, MSWMSs experience different sets of physical and social challenges (e.g., change in public policies and people's lifestyle) and operational strains. For instance, during pandemics, it is observed that there can be increased residential waste generation, as opposed to during storms or flooding where there are more other waste categories such as construction and demolition waste generated are from impacts to the built environment. Also, pandemics influence human interaction in the system more than affects the built environment, such as structures, buildings, and roads. Lastly, due to the ephemeral nature of the data generated during the pandemic, there is a lack of adequate information to properly plan for MSWMSs operation during a pandemic, making it difficult to develop best management practices for future pandemics. There is a need to understand and document the pandemic's impact in diverse MSWMSs along with their adaptive processes. To address this gap, this study seeks to promptly identify a broad range of waste management operational challenges during pandemic events and identify various adaptive measures undertaken by different MSWMSs. These results will guide researchers, private businesses, public solid waste agencies and regulators toward creating and implementing resilient waste management initiatives for pandemics.

3 A Three-Phase Framework to Characterize Adaptation Processes of Municipal Solid Waste Management Systems During the Pandemic

This research used a three-phase framework to characterize the adaptation process of different MSWMSs in response to their challenges during the COVID-19 pandemic (Fig. 2). The first phase focuses on the development of a baseline structure to capture the important characteristics of each MSWMSs. The second phase emphasises on the data collection process. It explains the process from deciding the target participants to the actual focus group interview. In the third phase, the team uses the developed baseline structure as the reference to understand the adaptation process of MSWMSs in terms of composition, control, and interdependencies.

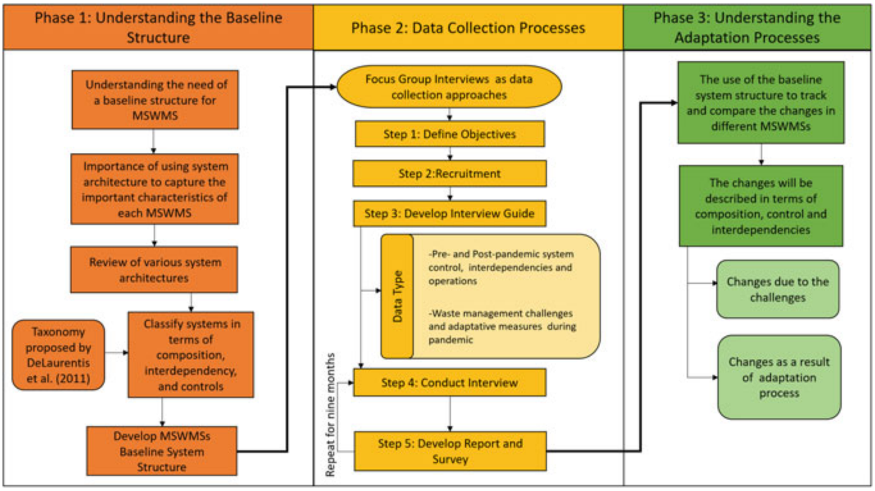

Fig. 2 Research framework

3.1 *Phase 1: Understanding the Baseline Structure*

The variations in the structure of MSWMS across different municipalities have made it difficult to observe the unique challenges and adaptive processes; therefore, it is important to use a baseline structure for comparison purposes. With the help of this baseline structure, we will capture important pre-pandemic and in-pandemic characteristics of each MSWMSs in question. In order to understand the system characteristics, this study explores various system classifications. For instance, Maier proposed a taxonomy based on the operational and managerial independence of the system's components [6]. According to Maier [6], characteristics of systems of systems such as geographic distribution and complexity of the components should not be used as classifiers of a system. Shenhar [12] also introduces a taxonomy in which the systems are classified according to four technology levels and three system scope levels. Given that MSWMSs vary from urban to rural settings in terms of entities, relationships, and control, we would use the taxonomy proposed by DeLaurentis et al. [4]. According to the authors, entities represent any physical or nonphysical independent systems. For example, waste collection companies, landfills, local government agencies, and material recovery facilities are independent system entities involved in MSWMSs. Relationships mean how the entities are interrelated and communicate with one another, and control refers to whether entities are granted autonomy or centrally controlled.

We will create our baseline system structure based on the understating of the proposed design variables (entities, interdependencies, and control). As seen in Fig. 3, each box represents all entities that are part of the MSWMS, while arrows represent the relationship between entities, and each color inside the box represents the control of each entity. Such visualization is used as the means to facilitate identifying

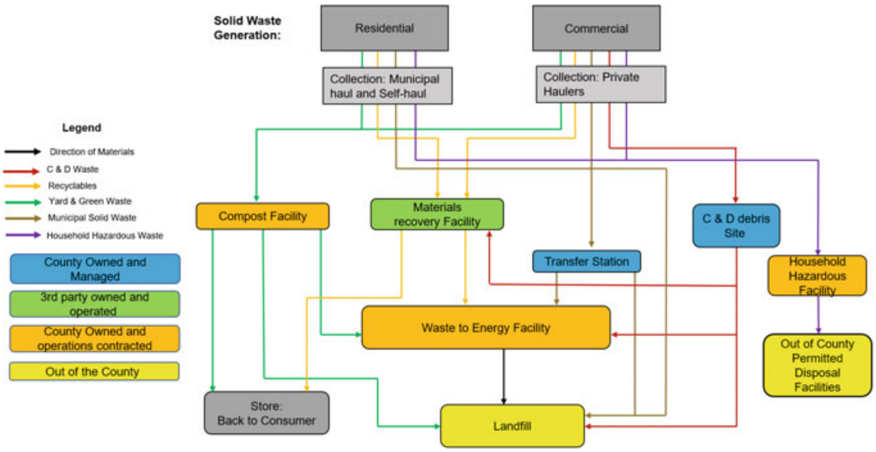

Fig. 3 Development of the baseline structure

the unique structure of different MSWMSs and detecting any emerging adaptation processes during the course of the pandemic. Furthermore, the development of the baseline structure helped us identify challenges and distinguish entities' emerging behaviors within their systems through comparison with future system structure during the pandemic.

3.2 Phase 2: Data Collection Processes

After understating the importance of a baseline structure and developing it for each participating MSWMS (Fig. 3), the team started the data collection process. This research used focus group interviews as the data collection approach. The team decided to target U.S. states that were the most impacted such as Florida, New York, and California, to obtain as much insight as possible. As part of the selection process of participating systems, we have selected several MSWMS with varying urbanization levels since the effects of this pandemic and the responses would also vary from urban to rural settings. Since we wanted to understand the adaptation process of the MSWMS, we decided to perform this data collection throught May 2020 until February 2021 via video and audio conference. This timeline would help us understand the evolution of both challenges and adaptive measures. After defining the objectives and target participants, we were able to start the recruitment process. The recruitment of MSWMSs representatives from the areas of interest was conducted through email. Next, the interview guide was developed and provided during the kick-off meeting. During this session, the team explained each meeting's aim and devised the research questions in a sequence manner. By following this guide, the study obtained all necessary information for the research from each meeting and kept us in an hour limit interview. The study met with the participants once every month over nine months to collect as much data as possible. The questions formulated covered all the data types (management challenges, adaptive measures, and pre-and in-pandemic system structure) needed to fulfill the research objectives. Consequently, the study conducted online interviews following the developed interview guide to address the research's main goals. For accuracy purposes, each conducted research interview was digitally recorded and later transcribed into a report. This report would help recall all the interview questions and answers. The team also created a survey spreadsheet that was sent afterward to each participant to confirm our findings. The data collection process was repeated over nine months to capture various impacts on MSWMSs in different municipalities and observe how their responses evolve.

3.3 Phase 3: Understanding Adaptation Processes

MSWMS entities' challenges will change during the pandemic; therefore, their adaptative actions will also evolve over time. As such, it is important to track and understand the adaptive processes of MSWMSs during a pandemic as a time-bound process. Using the system architecture developed in Phase 1, this study captured any changes in the structures of the MSWMSs as a result of entities' measures. Using the proposed system architecture, we have observed and documented system changes in terms of interdependency, composition, and control. For example, local solid waste authorities can loosen up contractual requirements for waste collection service providers by temporarily changing waste pickup policies so that the waste collectors can focus more on collecting residential waste [1]. This is an example of changes in the system control. Another example of a possible change that can be seen using the system architecture is the change waste stream (e.g., an increase in recycling stream and a decrease of household hazardous waste stream) as changes in interdependency because MSWMS would prioritize the waste stream that has increased and thus changed the flow of the materials between facilities to withstand this change in volume. As for changes in composition, this can be seen, for example, if there are any suspension services or facilities' closure as it would mean that the entity would not perform its function.

4 Adaptation of Municipal Solid Waste Management Systems During the Pandemic

4.1 Challenges and Adaptations of MSWMSs

Although MSWMSs' structure can vary across municipalities, they can also share common functions and operations to provide waste services. After establishing baseline structures of all of the participating MSWMSs, the team was able to find the major challenges that affect the waste management systems and their associated adaptive measures. The study divides these challenges into several categories such as health challenges, business continuity challenges, waste collection, waste landfilling, and recycling challenges. Tables 1 and 2 summarize the causes of the challenges, the challenges themselves, and their related adaptive measure. As seen in these tables, the major challenges were found in the health category.

4.2 Unique Adaptation Processes to Different MSWMSs

The structure of different MSWMSs varies across municipalities from urban to rural settings in terms of entities, interdependencies, and control. In other words, no MSWMS is the same in terms of entities, interdependencies, and control across different municipalities. For instance, an MSWMS from Florida is known to have waste incineration facilities; however, an MSWMS in California does not have this type of entity due to its state regulations. Since they do not have the same entities, the treatment of waste would be different, and thus interdependencies would not be the same. The study also found differences in the system structure even within the same state. For example, there are two systems in Florida, System 1 and System 2. Both have solid waste, yard waste, and recyclables streams. System 1 has a transfer station, yard waste site, and landfill that the county owns and manages. It also has a material processing facility and waste incineration facility that is county-owned, but its operations are contracted. In contrast, System 2 does not have a waste incineration facility since its main focus is yard waste and recyclables. Compare to System 1, the landfill and yard waste site is county owns, and operations contracted. The material recovery facility is owned and operated by a private party. Such different natures of the systems often make them take different adaptation processes even in response to the same challenge. For example, we have two MSWMS, one from Florida and the other from California. The Florida system structure's control and composition can be seen in Table 3. It is important to mention that this system's primary means of disposal is the waste incineration facility. Unlike California's system, Florida municipal and private collection services collect both residential and commercial waste jointly. As for the recyclables, this waste stream is self-haul to the recycling drop-off centers of the county. The California system structure's control and composition can also be seen in Table 4. The main difference between these systems is that the California

Table 1 Major health challenges in the MSWMSs

Waste management categories	Causes	Challenges	Adaptive measure (changed system characteristics)
Waste collection	Business shutdown	A decrease in commercial waste	• Re-routed the trucks to make them more efficient (entity)
			• Cutback on overtime on the commercial side (control)
	Stay at home ordinances	Increase in residential waste	• Shift resources from the commercial side to residential collection (control and interdependencies)
			• Increase operating hours, drivers, trucks, and trips (entities and control)
Waste recycling	Recycling contamination	Improper disposal of plastics that may expose workers	• A temporary ban on plastics (control)
			• Enforce inspection of materials and acceptance of certain items only (e.g., soft plastic) (control and entities)
			• Educational outreach to create awareness on accepted materials (–)
Waste landfilling	Increase of waste generated	Large number of customers at landfill	• Customers wait in vehicles while staff unloads (–)
			• Increase in operational hours to meet high demand (entities and control)

(–) No relevant characteristics for this adaptive measure

system does not have a waste incineration facility. The reason behind this is that the state of California is reducing the amount of waste incineration to help reduce air pollution [11].

Both systems were impacted with the same challenge, recycling contamination. However, their responses were different due to their composition. Since the Florida system owns a waste-to-energy (WTE) facility and it is their primary means of disposal, the system decides to change the correlation from the recycling drop-off center and material recovery facility to the waste incineration. The contaminated

Table 2 General waste management challenges affecting MSWMSS and its adaptive measures

Waste management categories	Causes	Challenges	Adaptive measure (changed system characteristics)
Health challenges	High public demand	Limited PPE	• Produced their own reusable masks (–)
			• Got supplies from other sources (entities and interdependencies)
	Closed area and limited space in facilities	Difficulty in achieving social distancing	• Enforced use of masks and hand sanitizers (control)
			• Install physical barriers, for example, by canceling face-to-face meetings and by not sharing vehicles (entities)
			• Rotate shifts for staff working from home and office (control)
			• Staggered employees start times (control)
			• A shutdown of common areas (interdependencies)
			• Suspended cash transactions and enforced online and card transactions (entity and control)
	Staff test positive for COVID-19	Reduce of field operatives	• Cross-training more staff in case someone needs to be isolated (–)
			• Isolated any staff that was in contact with sick employees (–)
			• Conducted daily screening activities (–)

(–) No relevant characteristics for this adaptive measure

recyclables were taken to the WTE facility (Fig. 4). In other words, they temporarily suspend services of the materials recovery facility. While California's system offers mainly recycling and composting services. As an adaption to the recycling contamination, they treated the recyclables at the material recovery facility; however, to avoid workers' exposure, recyclables are left for up to 3 days before sorting (Fig. 5).

Table 3 Florida system structure's control and composition

Entities	County owned and managed	County owned but operations contracted	Third-party owned and operated	Out of the county
Collection services	✓		✓	
Recycling drop-off centers	✓			
Material recovery facility			✓	
Waste incineration facility		✓		
Yard waste processing facility		✓		
Household hazardous collection center	✓			
Collection point center		✓		
Landfill		✓		

Table 4 California system structure's control and composition

Entities	County owned and managed	County owned but operations contracted	Third-party owned and operated	Out of the county
Residential collection services	✓			
Commercial collection services			✓	
Material recovery facility		✓		
Compost facility		✓		
Compost processing facility		✓		
Transfer station		✓		
Landfill			✓	

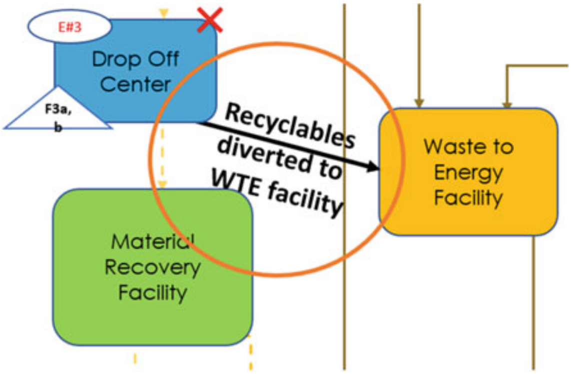

Fig. 4 Municipal solid waste management system of Florida

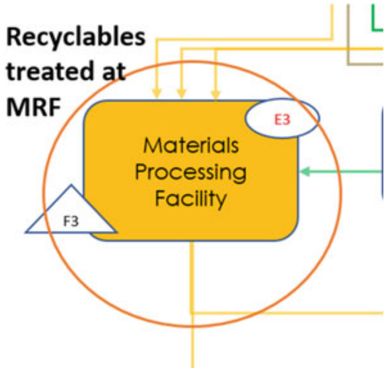

Fig. 5 Municipal solid waste management system of California

5 Discussion and Conclusion

The resilience of waste management systems is an indispensable factor of public safety and sanitation in their corresponding range. After reviewing prior studies on the resilience of municipal solid waste management systems, it seems that it is not possible to apply these findings to the development of strategies for pandemic events since prior studies focus on precedent events such as natural disasters. To address this gap, this study proposed and developed a three-phase framework to understand the adaptation processes of MSWMSs with respect to their challenges during the pandemic. In Phase 1, the team develops the baseline structure and highlights the importance of using system architecture to capture the important characteristics of each MSWMS. Using DeLaurenti's proposed taxonomy of system architectures, we were able to classify systems in terms of composition, interdependency, and controls. The next step was the data collection process. As previously explained, this study used the focus group interview as the primary approach. The data collection frequency was of once every month over nine months. In the last phase, the team used the system architecture adopted in Phase 1 to track and compare changes in different MSWMSs in terms of composition, interdependency, and control. The study learned that the main waste categories that had the most challenges were waste landfilling, waste collection, recycling, and health challenges. This study also found that even though MSWMSs would have the same challenge, they may respond differently depending on their composition, interdependencies, control, or other regional factors. Just as seen previously, the coronavirus pandemic has brought about various emerging challenges that most MSWMSs have never experienced. The collection of knowledge from past disaster events is important to develop resilience strategies for MSWMSs. In addition, understanding the impact of the pandemic in terms of system characteristics will facilitate the development of guidelines more relevant to different MSWMSs for their future preparation. That is, MSWMSs can learn something from the cases of other MSWMSs by referring to their relevant system characteristics.

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Gordie Howe International Bridge Construction Anxieties—The Bridge

R. Pickle and A. van Rooyen

1 Introduction

1.1 The Project

The Gordie Howe International Bridge project consists of four components—the Canadian Port of Entry, the Bridge itself, the US Port of Entry and the Michigan Interchange on I-75. The Project is being delivered through a Public–Private Partnership Agreement (P3). The design phase of the project commenced in July, 2018, with site preparation works by the private-sector partner beginning on both sides of the river in January, 2019.

1.2 The Bridge

The Gordie Howe International Bridge will be a six-lane cable stayed bridge, providing three Canada-bound lanes and three US-bound lanes over the Detroit River from Windsor ON to Detroit MI. The bridge will provide a direct connection from Highway 401 in Ontario to Interstate 75 in Michigan. The bridge will have a clear span of at least 853 m (2798 ft) across the Detroit River with no piers in the water. Two approach bridges, one on each side, will connect the main span to the Canadian Port of Entry and the US Port of Entry. The crossing, including the bridge and approaches, will be approximately 2.5 km in length. This cable stayed bridge will be the 6th longest in the world, the longest in North America and will be the longest composite cable stayed bridge in the world, with out—of—the—river drilled shaft

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foundations and concrete towers at 218 m (715′) height. The approach bridges will be all concrete design, 11 spans on US side, 10 spans on CA side, with precast concrete girders and drilled shaft/driven pile foundations.

1.3 Geotechnical Site Conditions

1.3.1 Existing Geotechnical Conditions

The existing site is relatively flat, with ground surface elevations between 178 and 179 m. The bedrock consists of Dolomitic limestone laying approximately 30 m below the ground surface. The overburden soils consist of fill material, soft to firm clayey silt to silty clay deposits underlain by lower compact to very dense granular deposits or hard silty clay till (hard pan). The silty clay at the project site is highly susceptible to rapid deterioration when exposed to elements, weathering, or when subjected to construction traffic.

Artesian and high-water table conditions exist on both sides of the river, with artesian groundwater pressures equivalent to a static water head of approximately 5 m above the existing ground surface. In areas where the bedrock is covered by silty or sandy clay layers, artesian conditions are expected to occur at, or nominally above, the bottom of the soft clay later. Where the bedrock is covered by thick layers of clayey till, it is expected that artesian conditions will occur at or nominally above the rock surface.

1.3.2 Geotechnical Testing

Initial geotechnical data to support engineering design was provided by WDBA. Supplementary investigations were performed by BNA and the Geotechnical Engineers of Record to allow for confirmation of soil and bedrock strata and groundwater conditions at the final location of the Canadian Main Bridge and Side Span and Anchor Span foundations. Additional soil samples and rock cores allowed for refining of parameters for the geotechnical assessments necessary for final foundation design.

1.4 Foundations

1.4.1 Tower Foundations

The main Bridge tower is an A-frame concrete structure with each of the two legs supported on a hexagonal pile cap. The pile caps are connected by a tower tie beam and are each supported by six cast-in-place reinforced concrete drilled pile foundations, with one drilled foundation located at each corner. The drilled shaft casings extend a minimum of 150 mm into competent bedrock and have a diameter of approximately 3162 mm in the overburden, with the diameter slightly decreasing in the bedrock. The lower part of each shaft is a 3000 mm diameter rock socket with a depth of 4.5 m below the tip of the casing.

1.4.2 Side Span and Anchor Span Foundations

The completed Bridge will have two side span piers and one anchor span pier on each side of the river. The side span piers are located at 258.5 and 318.5 m away from the tower and the anchor pier is located approximately 357 m from the main tower. The foundations of the side span and anchor piers are drilled shaft foundations with concrete shaft diameters of 3162 mm at the top of drilled shafts on the Canadian side and 3000 mm on the US side. The casings extend a minimum of 150 mm into the bedrock. The lower parts of the shafts consist of a 4.8 m deep rock socket with a dimeter of 3000 mm for the Canadian foundations and 2850 mm for the US foundations.

2 Construction

2.1 Equipment

Drilling for caisson excavations was completed using the Bauer BG55 drilling rig and Watson 3110 Drilling Rig. The steel casings were then advanced using an ICE 44-50 vibratory hammer. Drilling within the casings was completed using soil augers within the overburden, rock augers for rock drilling, and core barrels for the drilling of the rock socket and to remove obstructions.

Concrete was pumped using a reciprocating pump and tremie pipe.

2.2 Materials

2.2.1 Shaft Casing

The drilled shaft casings for the side span and anchor pier footings are CSA G30.18-09 Grade 400W (400 MPa) sacrificial steel casings as per OPSS 1400. The permanent casing for the main bridge tower footings is CSA G40.21 Grade 350W (350 MPa) steel with wall thickness of 19.0 mm.

2.2.2 Reinforcing Steel

For the Canadian tower shafts, Ontario Provincial Standard Specification, OPS 1440, Steel Reinforcement for Concrete specifies the supply of reinforcing steel in accordance with CSA G30.18, Grade 500W.

For the U.S. tower shafts the reinforcing steel shall be ASTM A615/A615M Grade 60/420 for the hoops and ASTMA615/A615M Grade 75/515 for the vertical bars.

The reinforcing steel used for the Canadian back span drilled shafts is CSA G30.18-09 Grade 400W (400 MPa) or 500W (500 MPa) as per OPSS 1440.

For the main bridge tower drilled foundations, steel reinforcement is a rebar cage with two layers, with 181 mm of clear cover on either side of the cage in the shaft up to the beginning elevation of the rock socket after which it is reduced to 100 mm. The first section of reinforcement extends to 7300 mm below the bottom of the footing with the outer layer consisting of 40 bundles of 55M bars and bundled 25M hoops. The inner rebar cage consists of 40 bundles of 55M bars and 15M hoops. Only the outer layer continues past the first section, with the second section consisting of 40 bundles of 55M bars and bundled 25M hoops. The third section extends from a depth of 21,350 mm to the bottom of the shaft and consists of 32 bundles of 55M bars and bundled 25M hoops.

For side span foundations, steel reinforcement consists of a rebar cage with two layers, with an outer layer diameter of 2500 mm and an inner layer diameter of 2033 mm. The outer layer reinforcing consists of 36 bundles of 35M bars with 25M and 15M hoops. The inner layer reinforcing consists of 24 bundles of 35M bars and 15M hoops. The inner layer extends to 11,000 mm below the bottom of the footing, with the outer layer continuing past this point to the bottom of the shaft. The number of bars used in each layer of the outer reinforcement decreases gradually along the depth of the shaft, starting with four and ending with two bars in each bundle.

For anchor pier foundations, steel reinforcement again consists of a rebar cage with two layers with an outer layer diameter of 2580 mm and an inner layer diameter of 2113 mm. The outer layer consists of 36 bundles of 35M bars with 25M hoops. The inner layer consists of 24 bundles of 35M bars and 15M hoops. The inner layer extends to 6500 mm past the bottom of the footing, after which the outer layer alone continues to the bottom of the shaft. The number of bars used in each layer of the outer reinforcement decreases gradually along the depth of the shaft, starting with four and ending with two bars in each bundle.

2.2.3 Concrete

According to the project specifications, the main tower concrete has 56-day compressive strength of 60.0 MPa (8702 psi) and the main tower foundation shaft and drilled shaft concrete have 28-day compressive strength of 41.4 MPa (6000 psi). The side span pier and anchor pier columns, caps, and footings concrete have 28-day compressive strength of 41.4 MPa (6000 psi).

3 Construction Means and Methods

3.1 Shafts

The steel casings for each of the drilled shafts were installed in three sections using a drill rig and vibratory hammer to drive them below the top of grade. Each section was advanced using the vibratory hammer after which drilling below the shaft tip was conducted using an auger and the subsequent section was attached via welding. After the refusal of the final section of casing in the bedrock, the rock socket was then drilled below the tip of the casing, with final drilling using a core barrel.

Following the drilling of each of the shafts, it was necessary to pressure grout the bedrock below the shaft bottom. This was accomplished by advancing one post construction drill through one of eight Crosshole Sonic Log tubes pre-installed in the shaft. Once the bedrock was reached, the drilled section was pressure grouted through one of the CSL tubes. The grouting procedure was then repeated through an opposing tube after which the CSL tubes were filled with non-pressurized grout using a tremie tube and capped off.

Prior to the installation of the shaft rebar cages, it was necessary to confirm that the project specifications for base cleanliness were met. This was accomplished by cleaning the bottom of the shaft excavations using an airlift and cleanout bucket. Base cleanliness and the thickness of the sediment layer present was then confirmed for each shaft using a Shaft Quantitative Inspection Device (SQUID) testing. Base sounding was then completed, immediately, as well as after the installation of the rebar cage, and prior to concrete placement.

3.2 Reinforcement and Concrete Placement

Prefabricated steel rebar cages were lowered into each shaft immediately after the completion of the shaft base sounding using a main and trailing crane. Once each cage was at the specified height, support walers, clevis, and PT bars were installed and tightened. The rebar cage was then released from the crane and secured using lock nuts.

An additional base sounding was completed to ensure that base condition requirements had been met. Concrete was placed continuously through a tremie and continued past the top of the casing until good quality concrete was evident. Overpoured concrete was then demolished to reach sound concrete at the final top of shaft elevation. If the overpoured concrete was observed to be of low quality during demolition, additional concrete was removed and an epoxy resin applied to act as a bonding agent before the pouring of additional top-up concrete.

After the shaft concrete was poured, the surrounding ground was excavated to allow for the construction of the shaft collar mud slab and shaft concrete collar.

3.3 Post-construction

Testing was required post-construction to ensure that drilled shafts met the requirements set out in the project specifications. After shaft concrete is poured, Crosshole Sonic Log (CSL) and Thermal Integrity Profile (TIP) tests were performed to ensure that no debris had become inclusions within the concrete during its placement.

Additionally, post construction coring was required for the shafts of the main tower, side span piers, and anchor piers. HQ sized (96 mm diameter) cores were advanced to extract 63.5 mm diameter samples from 0.6 m above the toe of the shaft to 6 m below the toe to verify the condition of the interface between the shaft concrete and rock and the bedrock below the toe. The recovered cores were visually inspected to check for honeycombing, segregation, voids, or inclusions within the concrete.

4 Construction Issues

4.1 Side Span Shaft P08

Issues developed with the installation of the third section of the P08 casing, which was vibrated and advanced to refusal at a location above the bedrock, approximately 30 m below grade. Following the refusal of the casing, the inside of the shaft was drilled to 27.5 m below the top of the casing using a 3.0 m auger. An obstruction was encountered at this depth and drilling could not continue with the auger. A 2.4 m drilling bucket and 3.0 m diameter core barrel were successfully used to advance the drilling further. Drilling was continued with a 2.4 m diameter core barrel and 3.0 m spate auger, but this resulted in the auger breaking within the casing at its connection point to the Kelly bar. The removal work was undertaken by the Contractor, who successfully removed the auger by drilling into it with a smaller auger.

Following the removal of the auger, it was possible to advance tools to 37.7 m below grade and to complete drilling to confirm the location of the bedrock which was approximately 100 mm below the tip of the casing, thus requiring further advancement to achieve the required embedment. The casing was advanced a total of 111 mm, which resulted in 11 mm embedment. As it could not be advanced further it was necessary to pour a concrete plug.

4.1.1 Holes in P08 Casing

Following the P08 casing installation, airlift cleaning of the shaft was completed before rebar cage placement. During this cleaning, three holes, likely due to installation issues, were found in the casing. The holes were located one above the other 10 m above the bedrock, with dimensions of approximately 100 mm in height and 300 mm in width.

4.1.2 Damage to P08 Casing Seal

Further damage was identified at the tip of the P08 casing, which resulted in a decrease in length of the casing of approximately 800 mm and a gap between the bottom of the casing and bedrock. This caused water loss, and the required positive waterhead of 1.5 m above the maximum recorded artesian pressure could not be maintained during drilling of the shaft, with water observed to be 200 mm below the required maximum pressure.

4.1.3 P08 Concrete Quality

After the installation of the P08 rebar cage and subsequent concrete pour, the over-poured latent concrete was found to be of lower quality than required. The concrete was chipped down farther than expected to reach clean, sound concrete. It was determined that the concrete was of poor quality based on the consistency of aggregate presence and distribution and the relatively short time and ease of effort expended when the concrete was chipped and scored with jackhammers.

4.1.4 P08 Shaft Leaking

Following the placement of the top up concrete at P08, leaking was identified within the shaft during the post construction extraction of concrete cores.

4.2 Anchor Span Shaft P12

The P12 casing was installed successfully, with refusal occurring approximately 30.8 m below grade. Drilling within the casing was then advanced to 33.5 m below the top of the casing using a 3.0 m drilling bucket. The bedrock was located at a depth of 39.1 m after which a core barrel was advanced to 39.7 m below the top of the casing and the shaft concrete plug was poured. During subsequent drilling, the 2.84 m auger, that was in use, broke within the shaft at its connection with the Kelly bar. Various attempts were made to remove the auger, with successful removal eventually being made possible by cutting the auger into pieces and removing them using a crane and grappling hook.

4.2.1 P12 Rock Failure

After the installation of the P12 casing, a large rock failure was found below the casing bottom by the Contractor. This resulted in a large gap between the bottom of the casing and the bedrock which allowed for the inflow of material into the base of the caisson and prevented the Contractor from meeting the requirements for base cleanliness.

4.2.2 P12 Micropile Drainage Layer

Further issues arose after the P12 concrete pour was completed with water being observed to be flowing down the side of the concrete when the casing was cut to its final elevation. Additionally, moisture was observed adjacent to the casing and around the top of the Manchette tubes which had been used to pressure grout the P12 rock failure.

4.2.3 P12 Concrete Quality

After the installation of the P12 rebar cage and subsequent concrete pour, the over-poured latent concrete was found to be of lower quality than expected. The concrete was chipped down farther than expected to reach clean, sound concrete. It was determined that the concrete was of poor quality based on the consistency of aggregate presence and distribution and the ease of effort expended when the concrete was chipped and scored with jackhammers.

5 Investigations

5.1 Side Span Shaft P08

5.1.1 P08 Shaft Casing Installation

Investigations were completed to determine the nature of the obstruction encountered during the drilling of P08. This necessitated the completion of a Sonic Caliper test on the shaft casing to investigate irregularities observed below a depth of 22 m. Additional testing was also completed after pouring the concrete plug. This involved completing a base sounding of the shaft, which was unsuccessful in determining the base and depth of the shaft due to the presence of a large amount of sediment. It was therefore necessary to determine the source of the sediment inflow into the shaft casing.

5.1.2 Holes in P08 Casing

In order to investigate the inflow of sediment that was encountered during the base sounding of shaft P08, the Contractor conducted a down-hole camera inspection of the shaft. The inspection showed that the steel casing had been ripped open, with rocks protruding inwards into the casing. Additional investigations were carried out by divers who observed that the holes were localized and that the casing had been heavily gouged in the surrounding area.

This damage was identified as the reason that the Contractor was unable to clean the base of the caisson to meet the project specification requirements for base cleanliness and it was noted that material would continue to build up over time. It was therefore deemed necessary to repair the holes to allow for successful airlift cleaning of the base.

5.1.3 Damage to P08 Casing Seal

Following the completion of the repairs, leak testing of the shaft was undertaken by the Contractor. The results of this testing indicated that although the holes had been repaired, there was another source of water outflow from the shaft. Divers undertook a video recording of the damage to the casing seal for further investigations. This recording showed tears in the steel casing in the area close to the tip and potential rocks protruding through the casing as well as poor visibility due to sediment build-up.

Airlift cleaning of the shaft base was proposed to determine if further build-up of sediment in the shaft was taking place. Only the south side of the shaft was cleaned with further airlifting not completed due to frequent blocking of the airlift with sediment, causing concern that soil sloughing was occurring. The shaft base was ultimately cleaned using a bailing bucket. A further camera inspection showed damage to the casing and open limestone joints, with the tip of the casing seen to have refused on glacial till approximately 0.8 m above the bedrock.

The resulting geotechnical condition was examined by the Geotechnical Engineers of Record, who assumed that no lateral soil resistance would be provided by the soil layer between the bedrock and 4.5 m above it. It was noted that if lateral resistance was shown through structural analysis to be vital in this section of soil, that mitigation measures would be required after the completion of construction.

Additional concerns were raised due to the potential for soil sloughing, but this risk could be assumed to be low if the testing proposed by BNA was passed. This testing was undertaken by the Contractor and involved further base cleaning, base sounding, and SQUID tests. Following the concrete pour, CSL and TIP tests were also completed along with optical and acoustic televiewing to verify the base conditions of the shaft.

5.1.4 Concrete Quality

Further investigations of the concrete quality in the shaft were undertaken as a result of the extent of concrete removal beyond the originally expected extent of latent concrete removal.

The CSL test results had identified an anomaly 16 m below the cut of elevation for the shaft. This anomaly was initially attributed to the reinforcing steel. This finding, in conjunction with the observations made during the removal of the over-pour, prompted additional investigations into the quality of the concrete.

HQ sized (63.5 mm diameter) cores from the surface to approximately 17 m depth were taken of the P08 concrete, after which water was observed to be leaking from the core hole. Honeycombing and low strength was observed in the extracted concrete cores between elevations of 161.6 and 160.2 m and water had filled the core hole at this location. It was assumed that the water had come from the bedrock, either through channels at the vertical rebar or between the steel casing and concrete surface and the water then emerged laterally through the honeycombed concrete in the core hole.

The effect on shaft durability of the P08 water leakage was also investigated. The corrosivity of water samples from the core hole was tested, with results showing low amounts of chlorides and sulfates unlikely to cause durability issues. Even so, it was still necessary to consider the risk due to the exposure of the steel rebar cage in the location where low strength concrete was encountered. To evaluate this, the corrosion loss of the steel bars was considered as if they were directly exposed to water with a pH of 7, lower than that of groundwater. This gave a conservative result of an estimated 1.2 mm corrosion loss on all surfaces.

5.2 Anchor Span Shaft P12

5.2.1 P12 Rock Failure

A down-hole camera inspection was completed by the Contractor and showed a large rock failure below the bottom of the P12 shaft casing which allowed material inflow into the caisson excavation. It was noted that sealing of the rock failure was required to allow for successful airlifting to the standard set out in the project specifications.

The sealing of the rock failure undertaken by grouting using a Manchett Tube system.

5.2.2 P12 Micropile Drainage Layer

Due to the observation of moisture after remedial micro-piling works, it was necessary to determine if the water was leaking from the Manchette tubes or from the surrounding ground. In order to investigate, holes with 1-in. diameters were dug around six Manchette bundles to expose the top 100–200 mm of the Manchette tubes. Additional test pits were also excavated. Upon inspection of the manchette bundles, small amounts of water were observed in the bottom of the holes. The soil at the bottom of the test pits was also wet but with no observed free water. It was noted that the manchette tubes themselves did not contain water, suggesting that the water was coming through the Manchette backfill material and not through the tubes.

In order to mitigate drainage issues at P12 and to prevent water ingress from impacting the shaft or footing, it was proposed to install a French drain with a 1.2 m wide ring of 20 mm Clear Stone and thickness of 300 mm around the perimeter of the drilled shaft above a layer of packed Granular A. The French Drain was to be entirely wrapped in Geotextile filter cloth and was to extend away from the drilled shaft easterly towards the Canadian Port of Entry.

6 Remedial Undertakings

6.1 Side Span Shaft P08

6.1.1 Holes in P08 Casing

The initial remedial work proposed for P08 involved the use of a 6 mm thick steel cover plate welded to the casing, at the locations of the various punctures and tears, after which the void behind the plate was pressure grouted using a pre-installed valve. These repair plans were altered after it was noted that attaching the plate by welding underwater would not be effective. A combination of welding and the use of J-bolts would prove to be a superior seal.

The patch plate used in the repair had a thickness of 9.5 mm with holes to install 19 mm J-bolts and pre-installed valves and pipes as necessary. Holes corresponding to those in the patch plates were cut by divers to facilitate connection with the J-bolts. The plates were installed first using J-bolts and then using a 6 mm fillet weld in locations where there was full contact between the casing and plate. In locations where the steel was irregularly shaped, the plates were cut to create a complete seal around each hole.

Once completed the welds were inspected using a down-hole camera and the voids behind the plates were pressure grouted. The pipes and valves were then removed. The bolt heads were then cut off and bolt holes were covered with small plates and welded shut.

6.1.2 Damage to P08 Casing Seal

Regarding the damage to the P08 casing seal, the shaft was over-reamed and air-lifted at the rock fracture elevation and shaft base in order to clean as much material as possible and reduce the potential for sloughing. A shaft sounding was completed 12 h after these activities and came back acceptable. It was then proposed by BNA that the shaft be scratched and airlifted prior to taking SQUID readings 24 h apart to check base cleanliness over time. Both tests came back acceptable. A third and final test was undertaken prior to the installation of the rebar cage and the concrete pour.

6.1.3 P08 Concrete Quality

The results of the CSL testing and the assessment of the cores extracted suggested that aggressive rehabilitation would be necessary being removal of additional concrete, in the southeast quadrant of the shaft, and repouring. Analysis, by the EOR, of the integrity of the concrete in P08 was undertaken based on two scenarios: remove and repour part of the shaft, do nothing. Comparison of the analysis of the two scenarios came to the conclusion that leaving the existing concrete was the preferred option.

Subsequently, BNA proposed cleaning of the top of the shaft and subsequent coating of the dried concrete with epoxy resin prior to topping up the shaft. The top-up concrete was of the same mix as that of the drilled shafts and was placed while the epoxy resin was still tacky to allow for it to act as a bonding agent and seal coating of the concrete surface at the construction joint.

6.1.4 P08 Shaft Leaking Impacts

Based on the evaluation of the corrosion loss expected due to water leaking within the P08 shaft, it was determined by the Durability Consultant that further mitigating actions were not required, given that the structural requirements were met and that the leaking core hole was filled with an appropriate repair material to mitigate the flow of water.

6.2 Anchor Span Shaft P12

6.2.1 P12 Rock Failure

In order to prevent unwanted inflow of material into the P12 caisson excavation, it was proposed that a grouting procedure be implemented to seal the rock failure. This procedure involved backfilling the rock socket and pouring a concrete plug prior to drilling and grouting to prevent infiltration of grout into the caisson. Six equidistant holes offset 0.75 m from the casing were drilled and fitted with 8 manchette tubes at varying depths in each hole. The manchette tubes were then used to pressure grout the void around the casing.

6.2.2 P12 Micropile Drainage Layer

The proposal to install a French Drain system to mitigate the drainage issues observed at P12 was evaluated and accepted and the French Drain was installed successfully.

6.2.3 P12 Concrete Quality

Due to the low quality of the over-poured concrete, it was deemed necessary to top up the shaft with concrete. BNA proposed cleaning of the top of the shaft and subsequent coating of the dried concrete with epoxy resin prior to topping up the shaft. The top-up concrete was of the same mix as that of the drilled shafts and was placed while the epoxy resin was still tacky to allow for it to act as a bonding agent and sealing coating within the concrete surface at the construction joint.

7 Shaft Acceptance

7.1 Side Span Shaft P08

7.1.1 Holes in P08 Casing

Following the repair of the holes in the P08 casing, the patch plates were inspected and found to provide an adequate seal. Additionally, the actual potential concrete cover remaining after the repairs was evaluated and it was noted that it was adequate for the rebar cage to be lowered. A down-hole camera inspection was then completed, and the bottom of the rock socket was cleaned. The additional damage that was identified during the inspection was repaired were required prior to the continuation of shaft construction.

7.1.2 Damage to P08 Casing Seal

Following the repairs to the P08 casing seal, SQUID tests were completed and indicated that no active sloughing or further sediment inflow into the shaft was taking place. Based on these results and structural analysis considering the revised geotechnical condition identified by the Geotechnical Engineers of Record, it was concluded that the shaft was structurally acceptable and that no further mitigating actions were required. The rebar cage was lowered, and the shaft concrete was poured. Subsequent TIP and CSL tests were conducted and yielded satisfactory results, indicating that material had not become dislodged and embedded in the concrete.

7.1.3 P08 Concrete Quality

Following the application of the epoxy resin and the top-up concrete pour, overpoured concrete was demolished and further construction continued on the pier footing.

7.1.4 P08 Shaft Leaking Impacts

Based on the evaluation of the concrete cores and water leakage, durability issues were not expected at the elevation where low strength concrete was observed. Structural analysis of the as-built condition of the shaft by the Engineer of Record indicated that the shaft was acceptable and the CSL tubes and core holes could be backfilled.

7.2 Anchor Span Shaft P12

7.2.1 P12 Rock Failure

Following remedial works to correct the rock failure encountered at P12, a final camera inspection was completed which showed good contact between the repair and underlying strata. Additionally, a base sounding was completed that indicated that the rock socket length and base cleanliness were in accordance with project requirements. Based on these results the rebar cage was lowered and concrete was poured.

7.2.2 P12 Micropile Drainage Layer

Following the installation of the French Drain at P12 the shaft was accepted and no further works were required to mitigate the observed drainage issues.

7.2.3 P12 Completion

Forming, placing rebar and pouring concrete for the footing was able to proceed upon completion of the remedial shaft works.

Technology-Oriented Innovation in Construction: A Conceptual Mapping Framework

A. Suliman, J. Rankin, and A. Caskey

1 Introduction

When compared to other industries, such as the automobile industry, the inefficiencies of the construction industry are apparent. Many of these inefficiencies can be attributed to the current onsite methods of construction [2]. Off-site Construction (OSC) is an innovative construction process where a significant portion of the construction work is completed at offsite fabrication shops before delivery for installation on site. Fabrication shops provide a properly-equipped, controlled work environment, with safe working conditions [1]. In Canada, off-site construction practices such as prefabrication and modular construction, are growing in acceptance, due to improved project quality, reduced material waste, reduced construction time and overall greater efficiency.

Despite the many potential benefits of OSC innovations, propagation and acceptance is still limited [7]. OSC represents only a small portion of the construction industry in Canada, as it does around the globe. Research has found that there is a need for the development of a strategic roadmap to direct efforts in OSC research, education, and innovation.

This research takes a crucial first step in developing a strategic OSC roadmap by developing a framework for mapping and benchmarking innovation in off-site construction. Benchmarking provides a necessary means for comparison and measuring progress in addition to supporting planning and implementation towards a future/desired state [3]. This research includes the development of a conceptual

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model necessary to represent, simplify and clarify complex real word conditions. The research project under consideration includes both technology-oriented and process-oriented innovation types. However, the research discussed in this paper will be limited to technology-oriented innovation.

1.1 Literature Review

A review of the existing literature included the review of many road mapping studies and planning initiatives specific to the construction industry. These included but were not limited to FIATECH [4], Seaden et al. [13], Rezgui and Zarli [11], and Kazi et al. [9]. The conducted review revealed the existence of good examples of roadmap models and frameworks. However, a model that is dedicated to or capable of accurately addressing and directing innovation in OSC was not found. In addition to that, the existing models tend to identify the future trends and desired state without assessing the current state or indicating the present level of construction innovation. A comprehensive review of the previous work is beyond the scope of this paper, but a brief review of the most relevant project is included below.

Froese [5] developed a strategic roadmap intended to direct efforts for research and development (R&D) in regards the construction innovation in the Canadian context. The roadmap presents three perspectives that convey three largely orthogonal issues associated with the R&D process: the application areas, the technology areas, and the innovation areas. These three perspectives have root in the conceptual framework introduced in Froese and Rankin [6]. It represents the most recent framework that developed and applied a roadmap to construction innovation within the Canadian context. In their paper, they introduced a multi-dimensional framework intended for modelling construction innovation and supporting a more comprehensive and richer understanding of the innovation process. Their framework outlines two sets of dimensions, the first set consists of three areas as follow:

1. **The Application Areas**. This dimension classifies the field of activity within the construction industry to which the innovation is targeted. The application areas are categorized into three classes: (1) *Management processes* (e.g., construction and project management), (2) *Project lifecycle processes* (e.g., design, procurement, production, maintenance, etc.), and (3) *Supporting processes* are considered to provide underlying foundation for all activities (e.g., collaboration, sustainability, and workforce, etc.).
2. **The Technology Areas**. This dimension categorizes technologies straightforwardly as being either *computational* or *non-computational.*
3. **The Innovation Areas**. This dimension explicitly models the various lifecycle stages that move innovations from a new idea to a new standard practice in five phases. These phases are data collection, technology development, conceptual development, production development, and application.

The first set represents the primary dimensions that are clearly defined, hence; they were used to develop roadmaps of construction innovation. The second set consisted of (1) *Organization*, (2) *Innovation objectives/drivers*, and (3) *Time*. This set of dimensions was not as well defined and thus was omitted from their framework.

This framework proposes a sound conceptualization of the current state of innovation but at a more conceptual level of detail and does not include elements of a specific benchmarking tool. For example, the subcategories of the application areas are only vaguely defined, relatively ambiguous, and incompatible classifications for some recent technology (e.g., Cyber Physical Systems do not fit this taxonomy as these systems relate to non-computational mechanisms that are controlled or monitored by digital computational technology). Furthermore, the framework does not provide subclass processes and/or granularity levels. Additionally, these subclass processes and levels are expected to vary between academic research, across different construction domains, and change along technology evolutions without defined boundaries. Thus, the research described in this paper attempts to build on their work to mitigate its limitations and accommodate the measuring complexity of innovation and potential technology and application advancements.

1.2 Research Mission

The mission of this research was to develop a conceptual framework based on a maturity model for the analysis of technological innovation in OSC. OSC innovation is defined, in this research, as "new applications of new or existing technologies to achieve improvements in activities related to OSC including time, cost, quality, safety, certainty, and automation." This work was conducted alongside the development of a similar maturity model for process/method innovation in OSC. The process/method model was beyond the scope of this paper and was therefore omitted.

This maturity model framework was intended to contribute to a larger road mapping study to support innovation in OSC within the Canadian context. Roadmapping as implied by the analogy to literal roadmaps, is a strategic visioning exercise intended to identify the current location/state, future location/state, and the path to get there. However, the most important part of roadmaps is the map itself which is the contribution of this study. The roadmap designed in this research is illustrated in Fig. 1. The figure outlines the roadmap in four components:

A. **Map (Framework)**: the framework that maps the applicable technologies.
B. **Current State (Benchmark)**: the reference that represents the maturity status at a specific time (i.e., the current time) with respect to a specific context (e.g., Canadian context).
C. **Future State (Matured State)**: the identified targets based on the measured maturity levels.
D. **The Road (Maturity Gaps)**: the maturity gaps identified based on levels of maturity models.

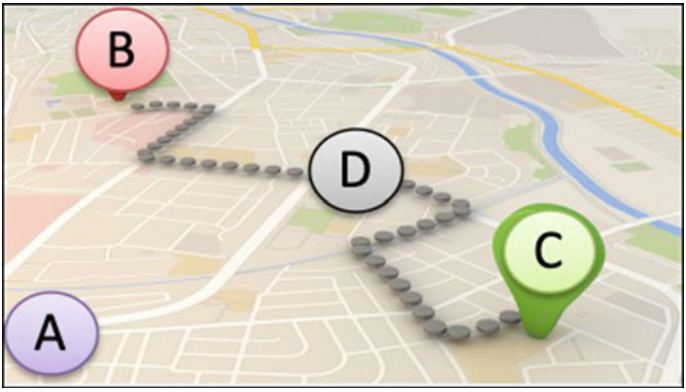

Fig. 1 The designed roadmap and its major components (Adopted from payment.com)

The maturity model framework developed in this research was modeled through technology-oriented conceptual frameworks as recommended by Deros [3]. This framework is intended to facilitate capturing the current state (benchmarking) and help in designing the roadmap for a desired future state. Where the scope of this research diverges from most other roadmapping initiatives, is that by itself, it is not intended to address future priorities or planning, but rather to provide a tool that can be useful for informed prioritization and planning. The development of the conceptual framework is described in the following section.

2 Developing the Technology Mapping Framework

To map the technology-oriented innovation in construction domain, the conceptual mapping model is divided into two facets, (1) Technology framework and (2) Maturity scales, as follows.

2.1 Technology Framework

From a geometrical conceptualization perspective, technology-oriented innovation is presented in a three-dimensional (3-D) space. The space includes technology, application, and innovation dimensions. As a 3-D space, the first two dimensions defined a kind of planimetric location, while the third defines the innovation level. This conceptual model is powerful in understanding and modelling the innovation process in construction. Similarly, a multi-dimensional framework can be modeled to map various aspects of technology-oriented innovation in OSC. In contrast to other multi dimensional frameworks, our model provides a distinction between

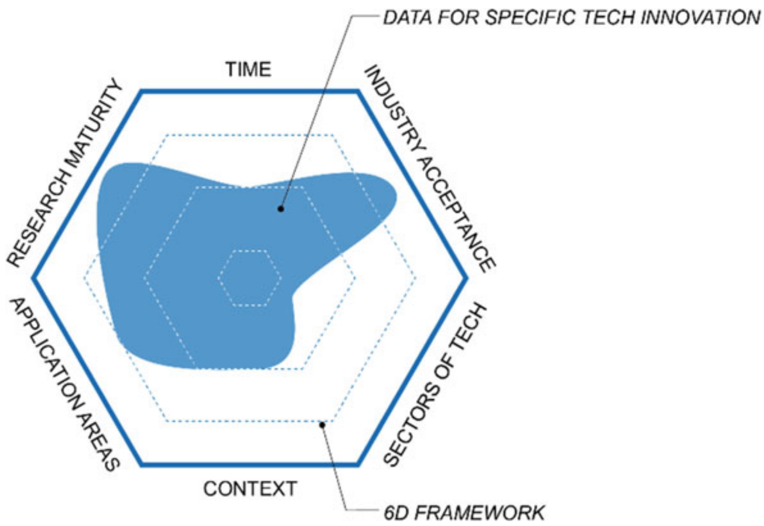

Fig. 2 The six-facets/dimensions of the technology mapping model

research maturity and industry acceptance to add additional accuracy and clarity in modelling and understanding the maturity of innovation at a given time. This resulting four-dimensional mapping model represents a snapshot in time within a certain scope/context. By adding two additional dimensions, time, and context, it becomes a six-dimensional model capable of capturing a more complete realization of the state of innovation. The time dimension allows for the identification of trends over time while, the context dimension defines specific boundaries to the captured trends. For example, the context dimension could account for the scope of the framework application or scalability based on the location and management/government levels (e.g., maturity may vary in Canada vs. Europe vs. Asia at the organization, municipality, or provincial levels). The proposed model is illustrated in Fig. 2.

The dimensions of the model in Fig. 2 are (1) technology areas, (2) application areas, (3) time, and (4) context. These four dimensions define the technology framework. In contrast, the innovation dimension is modeled in terms of maturity scales. This maturity is considered in two dimensions: (5) research maturity (academia) and (6) industry acceptance (practice). The acceptance level is selected to represent a scale of which the innovation can become a common practice. Although there is a similarity in the dimension names and purposes of the model of Froese and Rankin [6], the applied classification and aggregation approaches are different. It should also be noted that within the dimensions of Technology and Application Areas, the proposed model features are further sub-categorized. The first four dimensions are described in the following paragraphs:

Technology Area Dimension—this dimension has been sub categorized into five technological areas. This classification was inspired by the three-theme classification of technology proposed under the umbrella of the Fourth Industrial Revolution or

Industry 4.0 (4IR) which includes Industrial Production, Cyber-Physical Systems, and Digital and Computing Technologies [12]. Building on the 4IR technology themes this model categorizes OSC innovation into five areas:

(1) Digital computational technologies,
(2) Smart technologies,
(3) Cyber-physical technologies,
(4) Industry production technologies, and
(5) Supporting technologies.

The 4IR classification system describes digital technologies as those that live in the cyber environment, while industry production technologies are those that operate in the physical environment. Cyber physical technologies are viewed as those technologies that operate across both realms. In the proposed modified classification, a smart technologies classification is used to categorize the digital technologies that can develop self-decisions and/or take actions. Similarly, the supporting technologies classification is included to accommodate any existing or future technologies that do not neatly fit within any other category. Table 1 demonstrates how established and emerging OSC technologies fit within the described categories.

Application Area Dimension—this dimension has also been subcategorized into five levels that are within three project phases. This classification was inspired by the 4-P's management concept in software engineering [8]. The "**5-P's model**" identifies technological innovation implemented in OSC at five levels: *Project, Process, People, Physical resources,* and *Product*. Furthermore, the expected benefits from applying the different technologies are as follows, (i) increased certainty in planning processes; (ii) increased efficiency in the execution processes; and (iii) increased effectiveness (ease and accuracy of the monitoring processes). Therefore, as inspired by Newtown Square [10], the application areas of the technology groups are identified as the three management process groups (planning, execution, and monitoring) of construction across the different levels of the 5-P's model.

Table 1 The five technology areas of the technology dimension

Computational technologies	Smart technologies	Cyber physical technologies	Industry production technologies	Supporting technologies
• Building information modeling (BIM) • Simulation • 4D simulation • Integrated geospatial BIM (GEOBIM)	• Artificial intelligence • Internet of things • Big data • Block chain/smart contracts • Cloud/fog computing	• Mixed, immersive, augmented or virtual reality (MR/AR/VR) • Identification/localization (RFID/GPS) • Sensors • Computer vision • Laser scanning • Ground penetrating radar (GPR)	• 3D printing/additive manufacturing (AM) • Robotics	• Information and communication technologies (ICT) • Symantec wed • UAVs/GAVs • Mobile devices

2.2 Maturity-Based Scales

The maturity dimensions of the model include both **Research Maturity**, and **Industry Acceptance** dimensions which could be viewed as factors that push and pull innovation towards overall maturity. In terms of innovation within OSC, academic research could be seen to represents the innovation push, while industry adoption could be viewed as the pull. To measure the maturity of these two dimensions it is necessary to quantify innovation based on a scale. Froese and Rankin [6] proposed a five-level scale of innovation as data collection, technology development, conceptual development, production development, and application. For the purpose of this framework, Froese and Rankin's innovation scale is limited in application as it is not precise in its delineation of the phases of innovation nor dose it differentiate between research and practice maturity. These shortfalls are addressed in the alternative framework presented in Table 2 which is intended to provide a more accurate representation of innovation maturity.

Using this model, a measure of research maturity could be measured by sampling a representative set of on-going construction research in technologies (i.e., research projects at Canadian universities or as a common proxy, journal or conference papers published in relevant Canadian research fora).

Table 2 Maturity models for the academic research and industry acceptance

Maturity level	Research maturity (a representative sample of relevant papers/R&D projects)	Industry acceptance (level of use in the last "xx" projects)
1	**Basic research** (exploring/understanding): research intended to understand novel technologies and explore their application opportunities in construction domains	**Limited** ($X \leq 20\%$)
2	**Applied research** (innovative applications): research considered when the new technologies are being innovatively applied in construction applications	**Promising** (21–40%)
3	**Evaluation research** (performance assessment): research intended to review and assess previous studies in terms of the success, failure, costs, and benefits of the technologies applied in novel construction applications	**Adapted** (41–60%)
4	**Prototype development** (commercialization/transferability): research that includes a development of a prototype of modified or new technology that demonstrate transferability and commercialization possibility	**Implemented** (61–80%)
5	**Adoption research** (study of industry acceptance): the research intended identify the barriers and restrictions of a technology from being transferred/adopted in the industrial practices	**Accepted** ($X > 80\%$)

The industry acceptance levels proposed in our study was made adopted to simplify implementation and quantification. It is essentially a five-level scale based on the percentages of implementing a specific technology in a certain number of past projects within a specific context. The industry acceptance of a specific technology in construction can be measured by surveying a representative sample of OSC organizations. For example, in the last 100 OSC construction projects, 30 projects were implemented using Building Information Modeling (BIM technology) within the Canadian context. This measure would indicate that the level of BIM-adoption within OSC projects in Canada is 30%.

Appendix is a graphical representation of the technology mapping framework developed. As indicated earlier, the technology-oriented innovation includes two aspects (research maturity and industry acceptance). Each cell in the framework has upper and lower rows where the upper row is for the measured research maturity and the lower row is to document the measured industry acceptance. Each row has five space where each one is dedicated for a maturity level in a sequence from left to right. Hence, the value in each space indicates the number of collected responses (either from industry projects or academic papers) that satisfy the specific maturity level indicated by its location. For example, we may have 20 research papers about an "X" technology applied to project cost estimation. Six papers are of research maturity 1, four papers are of research maturity 2, eight papers are of research maturity 4, and two paper of the last maturity level. Based on this example, the upper row of the cell would be filled out as follows [**6|4|0|8|2**]. If the industry acceptance of the same technology was found to be of different levels, the same principles are applied. The received responses are documented in the lower row of the same cell; as an example of 20 responses, [**5|7|3|2|3**] where five responses were considered level 1 maturity, and so on.

3 Framework Use Demonstration

As explained above, the mapping framework for technological innovation in OSC was developed to measure two simultaneous states of innovation maturity: the research maturity, and industry acceptance of specific technologies.

In the typical case, the necessary information required to measure the **research maturity** could be collected by various means including a literature review and/or survey. A review of literature that highlight publications of completed and on-going research projects related to OSC technologies could serve as an appropriate indicator of the maturity. The relevant literature and/or research projects would need to be selected to define a specific time and context. For example, the current status (time dimension) of the Canadian context (context dimension). Since these types of publications are typically assigned to university-based researchers, with specific publication times and geographic context they provide a reliable accessible database to draw information from. Similarly, a survey circulated to academics, and research professionals within a certain time and context could serve to provide sufficient indication of research maturity regarding technological innovation.

The necessary information required to measure the **industry acceptance** could also be collected by various means, but research suggests an industry survey is most appropriate. In an ideal scenario, the information could be captured from a centralized database of recently completed projects within a certain context or region. However, such databases tend to be incomplete and rarely include specifics of the technologies implemented during the project. In lieu of a centralized database, a survey administered to a sample of construction companies would serve as a reasonable indication of industry acceptance of certain technological innovation in OSC. The survey should collect responses indicating the frequency of using/applying those technologies in the last "X" number of OSC projects.

Table 3 demonstrates, with an example, how the framework described in the previous section could be used to interpret the maturity based on the collection of the

Table 3 Technology-oriented innovation assessment in both academia and industry

Aspect	Example description	Assessment outcome	
		Framework	Maturity scale
Academia R&D project	This research explored the application of virtual reality headsets for on site BIM model verification by developing a VR headset prototype capable of showing workers the exact intended location and features of building elements	This research applies immersive visualization technology (that is part of cyber-physical technologies) to help improve the process and accuracy of construction. Therefore, this project is mapped under the process planning and virtual reality technology	**Level 4—applied** This project attempts to apply the virtual reality in prototype development. Hence, it is an applied research. The maturity is of level 4
Industry construction project	A construction organization was contacted for a survey participation. The question was as follows: *In the last 10 OSC projects, how many times the visualization (virtual reality) technology has been used to enhance product design process?* The response was 2 OSC project	The question measures the frequency of using the virtual reality technology to enhance the product design. Therefore, the response should be mapped under product planning and virtual reality technology	**Acceptance level is limited (level 1 ≤ 20%)** The survey responder indicated that the virtual reality technology was used for less than or equal to 20% in the last 10 OSC projects. Hence, the industry acceptance on that technology is limited and it was applied in one project

types of data described above. The example is intended to facilitate the understanding of the implementation of the developed map. It is designed to cover the technology frameworks and maturity models. The hypothetical assessment outcome presented in Table 3 is documented in the relevant framework cell provided in Appendix. The white cell in the framework is the one that has entries based on the hypothetical assessment result. While the values inside the cell correspond to the number of the surveyed projects, and the location of these numbers indicates the maturity level out of the five levels of the developed maturity scales.

4 Conclusions

This research was initiated to pave the road towards building a strategic roadmap of innovation in OSC. This paper presented the conceptual framework for measuring maturity within OSC technological innovation. It introduced a conceptual design for a maturity-based innovation road mapping. This roadmap consists of four components: map (framework), maturity models (scales), benchmark (current state), and maturity gaps (road to future state). The first two components were the focus of the study to date.

This model drew from previous works including Froese and Rankin [6] and the classification of the fourth industrial revolution (4IR) among other works. The presented framework model is intended to serve as a tool for benchmarking and recording advancements in various forms of technological innovation in OSC. The model allows for maturity to be recorded over time and between various contexts.

The applicability of this model was described through a proposed implementation approach with an explanatory example. Based on that, the developed framework has high potential to create a solid foundation towards developing a strategic technology-oriented innovation roadmap to inform efforts in OSC research and adoption in the construction industry.

Next steps in this research are exploring data collection through more extensive surveying of industry professionals and researchers. It will also explore more extensive means of data collection such as the development of an online building database specific to OSC.

Acknowledgements The authors would like to acknowledge the funding sources that made this research work possible: The Off-site Construction Research Center (OCRC) and the OSCO Construction Group.

Appendix

<table>
<tr><td colspan="2">The context</td><td colspan="5">Planning processes</td></tr>
<tr><td colspan="2">Technology-oriented innovation framework</td><td>P1</td><td>P2</td><td>P3</td><td>P4</td><td>P5</td></tr>
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Forecasting Budget Overruns by Productivity Variations in Electrical Construction

Fei Han, Susan M. Bogus, Heather Moore, and Su Zhang

1 Introduction

Cost forecasting is a challenge through the life cycle of construction projects and gains research attention in the areas of project controls and data-driven probabilistic forecasting [5, 10, 14]. Earned Value Management (EVM) is a project management technique that provides analytic metrics for tracking, analyzing, and evaluating construction project performance based on the earned value (EV, as where a project stands at) [16]. In EVM, there are two indicators for cost overrun analysis for an ongoing project. They are Cost Performance Index (CPI) and Estimate at Completion (EAC). The predicting power of EAC and CPI is dependent upon EV, whose value is often estimated using accounting data and empirical judgments in a given reporting period [15]. However, the two indicators mentioned above could lead to the lagging detection of cost risks and biased forecasting. The existing methods to estimate EV cannot capture the realistic job progress for the lack of considering the work productivity fluctuation during the reporting period.

This work proposes an extension of EVM systems for project cost forecasting via a productivity-driven approach. To that end, the authors focused on labor costs in work

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hours and argue that the realistic earned value of a project should be evaluated based on the physical percentage of work completed at current work productivity, independent of the hour budget. The work productivity is measured in hours expended per one unit of work completion, based on a standard method per American Society for Testing and Materials (ASTM) E2691 [1]. Then, the Estimated Hour at Completion (EHAC) approach that integrates the impact of labor productivity variations is proposed for the total hours' forecasts. Lastly, a case project demonstrates how the proposed EHAC approach can be used in the context of an electrical construction project. The anticipated results of this research contribute to the knowledge and practices of project controls by providing practitioners a tool to enhance the accuracy of the work progress evaluation and total hours forecasting from a productivity perspective.

2 Background

2.1 Cost Forecasting in EVM

In EVM- and project control-related literature, scholars address cost forecasting from different points of departure, such as the stability of CPI at specific points of project percent completion [11], EAC forecasting using the exponential smoothing technique [2], cost forecasting based on reference class (RC) databases [3], and the adaptive EAC combination [12].

The EVM system provides two forecasting indices: CPI and EAC, based on three performance metrics: the budget at completion (BAC) or the planned value, the earned value (EV), and the actual cost (AC). For a particular reporting period, the BAC represents the budgeted value of the work as planned. The EV represents the budgeted value of the work completed to date, and the AC shows the actual cost expended to accomplish the EV. CPI (the ratio of EV to AC) can be greater than one or less than one, reflecting that a project is over or under budget. EV provides project progress information which is accomplished in a measurable unit such as dollars and hours during a given time period [16]. However, the existing EVM forecasting methods have been criticized for lacking operational predictability. As a cumulative cost index, CPI cannot accurately account for the performance variation during the course of the project, but acts as an analytical value showing if potential cost overruns could occur [2].

Another type of cost forecasting technique, such as the FRISK approach, focuses on cost risk analysis by simulating the probabilistic costs based on the triangular probability distribution of project costs [5]. Monte Carlo simulation is often used to obtain the overall cost in a stochastic manner. The underlying assumption of these methods is that the uncertainty of a parameter of interest (i.e., costs associated with a chunk of work) is pre-determined (i.e., minimum, most likely, and maximum) per the baseline and historical project records. For complex projects, cost forecasting can be improved by integrating expert opinions with project data records using the Bayesian model [4]. The outcome is still stochastic as the experts' opinions/judgments about the probability of cost overruns need to be elicited and transferred to a prior distribution.

2.2 EV Measurement in EVM

In project management, EV is a measure of work progress, and this value is earned as the work is completed. The progressing techniques in EVM include the quantity of units installed, incremental milestones, start (50%)-finish (100%) estimation, or individual judgment [9, 13, 15, 17]. The earned value should reflect the actual work put in place instead of hours/dollars spent during the reporting period. The traditional units for EV include labor hours and dollars. For instance, electrical design work is expected to take 100 h as the budget (BAC). Upon 60 h spent on the design, the engineers have "earned" 60 h of value, which is equal to an EV of 60% to record the progress of the design work. However, the earned value calculated based on the dollar/hour amount may not reflect physical work output—the percentage completion of work activities. Suppose that the 60 h expended are associated with the prep work, such as site investigation and change orders which only contribute to 30% of the actual design output. The EV values estimated by dollars and hours alone can be misleading. In this case, a uniform unit that can reflect the variation of work productivity is needed.

2.3 Productivity Variation Measurement

Productivity is a primary variable in construction due to the uniqueness of projects, such as different work conditions and levels of craftsmanship, even though similar types of work are performed. In this case, the productivity is often measured against a "benchmark"—standard practices (e.g., production rates associated with different types of work) established per historical project records. With baseline productivity rates, project management practitioners can track the in-process productivity to evaluate the intended job performance variation. Another way to measure productivity is via a performance factor obtained from dividing the planned hours to complete a work package by the actual hours expended on that work. The performance factor ends up being either greater or less than one indicating of the work is being more or less efficient than scheduled [9].

A leading indicator of project cost overruns is labor productivity variations. Compared to relatively fixed costs, such as materials and overheads, labor costs could vary significantly due to disruptions (e.g., trade interferences and constructability issues) to the field work. The existing standard to measure such labor productivity variations is provided by ASTM E2691 [1].

Per ASTM E2691, the in-process productivity is computed as a ratio of the actual labor hours divided by the observed percent complete of the work to date, as shown in Eq. 1. In this case, the productivity measurement is hours driven in terms of how many hours it will take to complete one unit of work. In other words, high hour values per unit of work completion suggest low work efficiency in the field. If needed, the resultant labor hours can be converted to the dollar amount by multiplying the hours by hourly rates. Here the work represents task-level work packages of a project in the form of Work Breakdown Structure (WBS). For instance, the WBS for an electrical project can be broken down by work packages, such as rough-in, fixture, and panel installation. Equation 1 also applies to the productivity measurement at the work package level.

$$\text{Productivity} = \frac{\text{Actual Hours}}{(\text{Observed }\%\text{ Complete} \times 100)} \tag{1}$$

Similarly, the baseline productivity is given as the budgeted hours divided by "100," which means the planned hours to complete one percent of the work packages being tracked. Then, the in-process productivity can be compared with the baseline productivity to obtain the productivity variation by a designated reporting period of the project (e.g., weekly or monthly).

2.4 Research Gap

The EVM approaches for cost forecasting establish well-reasoned procedures for identifying warning signs of cost overruns. However, EVM applications are mainly focused on deterministic indexing at the project level. Cost overrun indicators that can guide field operations at the task level are less frequently addressed. Also, detecting overrun issues in a timely manner is challenging since the project financial data are not available until the end of billing cycles. Based on the financial data cycles, the resulting CPI and EAC are often too general to reveal cost risks, so they are considered less meaningful to guide project operations at the task level to react early to the risks.

The cost risks represent the consequences of various disruptions that prevent the actual work from being completed as scheduled. This challenge is particularly true for most subcontracting jobs such as electrical construction, where a significant amount of installation work (labor hours) is involved. So, besides dollar amount and hours, cost forecasting requires tracking how much actual work completion has deviated from the scheduled progress during the course of a project. The variations of work progress accomplished in a given reporting period (i.e., productivity) provide the new point of departure to measure EV—the key to cost forecasting under the EVM system, which is less frequently addressed in the current literature.

To improve the cost forecasting in construction, the authors develop an extension of EVM techniques by improving the EV assessment from the productivity perspective which will allow more reliable cost forecasting at the task level of project controls.

3 Methodologies

3.1 EV at Current Productivity

In this research, labor hours are used as the alternative performance measure of project costs given the following considerations. The labor hour is the primary metric used by field personnel to estimate the labor costs. Unlike a lump sum project cost that could "hide" labor-related cost variations, labor hours alone directly show how divergent the labor cost could be due to various disruptions to the field work. According to the field loading curve in Fig. 1 [9], labor hour variations often occur in electrical construction where electrician-involved installation work is intensive.

To measure in-process cost variations, this research proposes a concept of EV at Current Productivity (EVCP) that is defined as the observed amount of work that was completed with the actual amount of hours spent on it for a specified reporting period. Unlike the traditional cost-driven EV, EVCP emphasizes that the earned project value should be assessed from the field perspective given the current level of

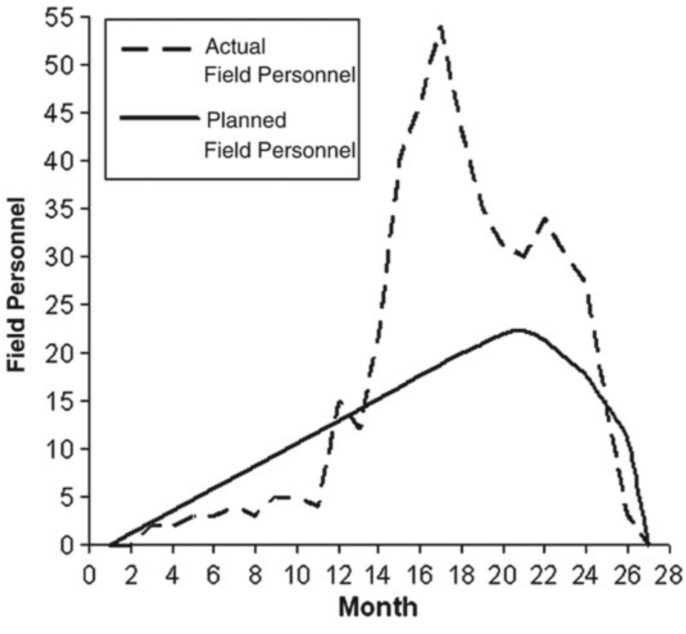

Fig. 1 Field labor loading curve for electrical construction [9]

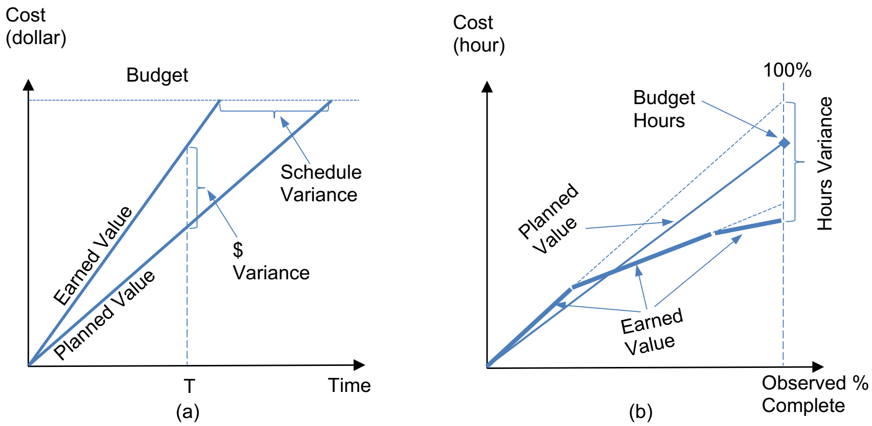

Fig. 2 EV in traditional EVM system and EV at current productivity

work productivity. The current productivity will be measured using Eq. 1 provided by ASTM E2691 since there is a direct relationship between EV and percent completion of actual work [8]. The observed % complete is independent of the budget and labor hours. When tracking the quantity installed, this value is simply the quantity installed to date divided by the planned quantity. For the work that cannot be quantified by units, determining the percent complete requires the subjective estimation of the physical work completion by seasoned field personnel such as superintendents and foremen. The key is that such judgments should come from those who have the best sense of the project from the field perspective, in particular having productivity variations taken into account [7]. The typical causes associated with the productivity variations include materials and equipment shortage, design issues, and lack of instruction and coordination [6].

Compared to traditional EVM, the proposed EVCP provides a field-oriented insight into project progress assessment. In the context of EVM shown in Fig. 2a, EV refers to a cumulative cost in dollar amount up to date (T). The cost is usually a lump sum, including labor, material, and overhead costs. Although determined within a duration of time, the EV suggests more about a monetary value than labor hours, and the associated physical project progress within the given timeframe. More often, traditional EV calculations do not indicate the manhour-specific outcome which is often referenced by field personnel (e.g., foremen and superintendents) to evaluate if a job is on the right track (i.e., under budget).

This research advocates that EVCP serves as a more appropriate metric for project progress reporting from the field perspective. As shown in Fig. 2b, the earned value represents physical work progress (observed percent completion) evaluated by field personnel. There are few EVM-related studies addressing details about work progress assessments via subjective judgment, even though decision-making based on observations and experiences is omnipresent in practice. For the observation-based approach, foremen and superintendents are the best candidates to place a percentage value on the amount of work that has been completed in a given reporting period. Moreover, the proposed EVCP acknowledges the variation of labor productivity from one reporting period to another. The current productivity is measured using Eq. 1 per ASTM E2691. In Fig. 2b, the planned value refers to the ideal situation that the work will be completed at a constant pace or the baseline productivity which can be obtained by having budget hours divided by 100 (100% complete). As far as the productivity variation, it can be observed from the changing slopes of the line segments in Fig. 2b. The slope of each line segment represents the current productivity by associating the percentage of the earned work completion with the hours expended on that completed work.

3.2 *Budget Overrun Forecasting via EHAC*

In EVM, EAC is the main CPI used to forecast the final project cost [15]. Equation 2 shows the generic form of EAC.

$$\text{EAC} = \text{AC} + (\text{BAC} - \text{EV}) \tag{2}$$

The EAC value shows the sum of the actual cost and budget left for the unfished part of work (BAC − EV). For the overrun detection, EAC could be misleading because the outcome will send a mixed message that a project could be over budget but ahead of schedule. As seen in Fig. 2a, the project has an earned value higher than the planned value (i.e., cost overrun) but then ends up finishing the budget earlier than the planned schedule. To reduce this illusion, a forecasting measure that solely focuses on the cost dimension is desirable.

In this research, Estimated Hour at Completion (EHAC) is proposed to forecast the total hours of a project that can reflect the productivity variations (EVCP). Suppose a project being tracked consists of work packages generated from the project WBS. And the progress of the work packages is evaluated as the work completed (WC) in the observed percent complete, as opposed to the work remaining (WR). The anticipated total hours—EHAC can be computed using Eq. 3.

$$\text{EHAC} = \text{AH}_{\text{wc}} + \frac{(\text{AH}_{\text{wc}})}{\%\ \text{Complete}} \times \text{WR} = \text{AH}_{\text{wc}} + \frac{(\text{AH}_{\text{wc}})(1 - \%\ \text{Complete})}{\%\ \text{Complete}} \tag{3}$$

where, AH_{wc} is the actual cumulative hours to date for the completed work; % Complete is the cumulative percent completion of work associated with a work package or project; WR refers to the work remaining to be complete and is calculated as (1–% Complete).

Per Eq. (3), the total hours of a project will be estimated as the sum of two pieces. One is the actual hours spent to date as the project progresses. The other is the forecasting piece that is used to calculate the hours it could take to complete the remaining portion of work at the current productivity (AH_{wc}/% Complete)—the pace of how the work has been completed.

Unlike the traditional EAC, the EHAC forecasting is independent of the original budget, which reduces the chances of manipulating the earned value (work completion) per the budget hours to make rosy forecasts. Also, EHAC is especially suitable for subcontractors whose business models are driven by labor costs since the EHAC outcomes reflect a strong field perspective about productivity variations associated with different types of work tasks and levels of work progress. The productivity-oriented tracking allows practitioners to stay informed about the task-level challenges and investigate the reasons behind them. As shown in Fig. 2b, EHAC at 100% job completion is obtained in a range of hours, suggesting the level of uncertainty for the project or particular portions of work. The wide hour variance suggests that a higher cost buffer is needed. Lastly, EHAC assessed at a regular (e.g., weekly) basis will project a trend about at what completion stages of projects the productivity tends to be stable (i.e., less variable EHAC). In this case, the stabilized productivity and associated hours can be used as reliable indicators to forecast future project performance for similar types of construction [11].

4 Case Study

4.1 Data Collection

This section illustrates how the proposed productivity-driven EHAC can be used for budget forecasting in electrical construction. The case project is from an electrical contractor that practiced productivity tracking using the ASTM E2691 approach. The selected project was tracked via its WBS consisting of work packages organized by six cost codes, including Feeders, DC String Wire, Inverters, Combiners, Modules, and Racking, which were consistently adopted by that contractor for solar-related projects. The project was budgeted with 1933 h and was completed with 2615 h. Table 1 shows partial data (three weeks) from the completed records over the total reporting period of nine weeks for the case project.

The budgeted hours were assigned by the field superintendents for task items grouped by the cost code they belong to. In addition to the baseline budget, the required data for each cost code include the weekly reports of the cumulative observed percentage completion and cumulative hours expended to date. The percentage completion data were directly measured and assigned by the superintendents as the realistic estimation of physical work progress independent of the actual hours. The percentage completion for each cost code is calculated as a weighted sum of the percentage complete associated with the tasks under the same cost code. Each task item is weighted based on its budgeted hours. The same weighted sum approach also

Table 1 Example of case project data

Cost code	Budgeted hours	Week 1		Week 2		Week 3	
		% complete	Actual hours to date	% complete	Actual hours to date	% complete	Actual hours to date
Feeders	76	66	72	66	84	66	94
DC string wire	224	0	0	0	5	19	84
Inverters	269	31	70	36	78	37	82
Combiners	108	35	36	39	42	51	50
Modules	604	3	48	45	258	82	605
Racking	652	91	338	97	441	99	775
Overall project	1933	40	564	56	908	71	1690

applies to the calculation of the overall percentage completion for the case project. The detailed procedures can be found in ASTM E2691 [1].

4.2 Earned Value at Current Productivity Curve

The current productivity for the overall project and cost codes is calculated using Eq. 1. The results are shown in an EVCP curve in Fig. 3. The current productivity of the overall project can be interpreted as follows. For the work progress achieved in week 1, it took on average 14.1 h to complete one unit of the work. The EVCP curves show that for the overall project, the hours expended per one unit of work increases notably in the first three weeks then trend up slowly until project completion. As far as the actual work efficiency, the project began at a fast pace, and then the productivity gradually declined as the project progressed. This trend reflects a situation that from the beginning of week 2, the electricians could not work at the initial pace due to some disturbances which are not discussed in this study. Subsequently, the productivity became relatively stable beginning in week 4, with the current productivity ranging from 22.27 to 26.64 h expended per one unit of work. Compared to the baseline productivity of 19.33 h per one unit of work (1933 divided by 100% complete), the project proceeded with a lower productivity than expected.

At the cost code level, apparent productivity fluctuations can be observed for Modules, Racking, and DC String Wire, contributing to productivity variations for the overall project. The Modules work experienced a slow start in week 1 before catching up in week 2 and continued to be steady until the end of the job. A similar trend can also be observed from the DC String Wire work. By contrast, the Racking work proceeded with a relatively fast pace in weeks 1 and 2 then continued with lower productivity. The current productivity for the Inverters, Feeders, and Combiners is

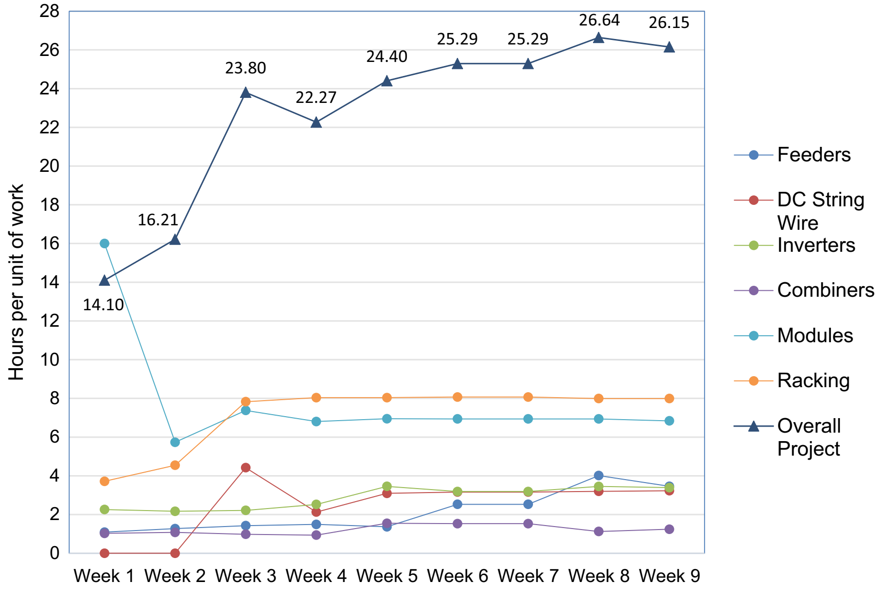

Fig. 3 EVCP curve

considered relatively steady over the entire reporting period. In practice, increased attention from the field management is required for the cost codes with high productivity variations. For the case project, heavily-weighed cost codes went towards the less productive side, thus leading to the budget overrun.

4.3 *Total Hours Forecasting*

Given the productivity variations, the total hours forecast consists of two parts: the actual hours to date and predictive hours for incomplete work. The proposed forecasting method—EHAC describes the impact of the productivity variations by calculating how many hours in total it could take if the remaining portion of the work was performed at the current productivity rate. Using Eq. 3, the weekly EHAC was computed for the overall project and its subordinate cost codes through the nine weeks of the reporting period.

Table 2 illustrates the EHAC by the cost codes whose total hours forecast vary dramatically as the result of the productivity variations. For instance, the possible EHAC for Modules ranges from 573 to 1600 h and is considered less predictable with the highest standard deviation of 328.3 h, compared to the budget of 604 h (shown in Table 1). This forecast means that the Modules work is sensitive to external disturbances to the labor productivity. An increased buffer is required when budgeting similar work for future projects. By contrast, the predictable cost codes

Table 2 EHAC forecasts by cost codes

Cost code	EHAC (hours)								Actual hours Wk9	Descriptive statistics		
	Wk1	Wk2	Wk3	Wk4	Wk5	Wk6	Wk7	Wk8		Min	Max	STD
Feeders	109	127	142	149	136	253	253	401	346	109	401	99.6
DC string wire	0	5	442	213	310	316	316	320	323	0	442	159.1
Inverters	226	217	222	252	346	319	319	345	339	217	346	57.0
Combiners	103	108	98	94	155	153	153	113	124	94	155	26.7
Modules	1600	573	738	680	695	694	694	694	684	573	1600	328.3
Racking	371	455	783	804	804	807	807	799	799	371	807	180.9

include Inverters and Combiners. The associated EHAC values are less varying and suggesting a stable productivity over the nine-week reporting period, given the relatively small standard deviation of 57.0 and 26.7 h, respectively. Thus, those two cost codes are not considered as the cost drivers for the budget overrun.

For the overall project, the weekly EHAC is presented in Fig. 4. The curve shows the total hours forecast at different percentage complete associated with each reporting period. From the beginning until the half-way completion of the project (weeks 1 and 2), the EHAC forecasts are optimistic as both 1410 and 1621 h are under the budget of 1933 h. Subsequently, the EHAC is predicted to go over the budget significantly, jumping from 1621 h (week 2) to 2380 h (week 3). Since then, the forecasts remain the same over-budget trend, with the EHAC values ranging from 2227 to 2664 h. The variance of the EHAC forecasts is higher than the difference

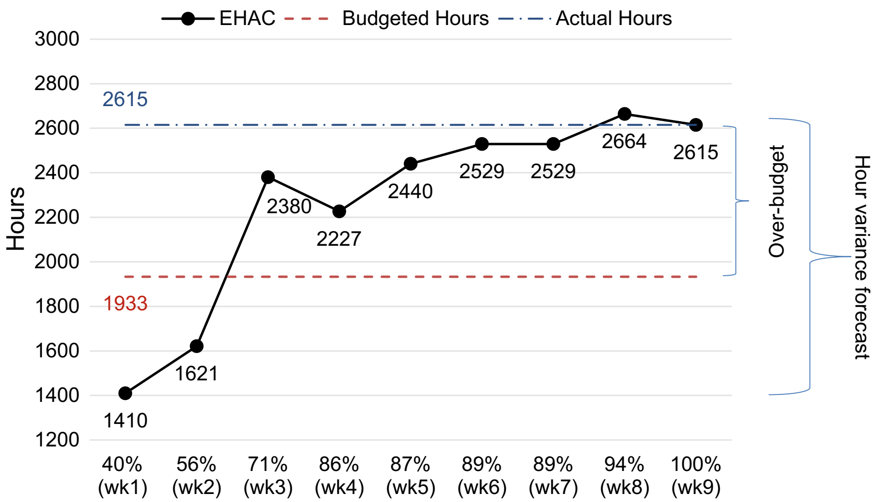

Fig. 4 Forecasted total hours at % completion

between the budgeted and actual hours, with a standard deviation of 459.3. This trend also indicates that the forecasting power of the EHAC is strong, especially when the project moves forward to the later project stages (e.g., 71% completion and afterward for the case project). Also, the later stages of the case project progressed with relatively stable productivity for most of the cost codes (seen in Fig. 3). From this perspective, the current productivity and its variations, as part of the EHAC approach, have proven to be a leading indicator of the total hours forecast.

5 Discussion and Conclusion

The authors examined the earned value of the case project from a productivity perspective, assuming that labor productivity is subject to change during construction. The top three cost codes with the highest divergent productivity are Modules, Racking, and DC String Wire. The direct impact of the declined productivity is to prevent the associated work from being completed as scheduled, therefore causing the budget overruns. The productivity tracking for specific work types provides field personnel a tool and data to detect potential overrun issues. To the best interests of contractors, the root causes behind the productivity variations and the resulting impacts can be investigated and used as evidence in the case of disputes over budget issues with owners or other contractors.

Based on the productivity measurement from ASTM E2691, this study proposed the EHAC approach for overall hour forecasts. The EHAC curve successfully shows the overbudget trend for the case project. Compared to CPI in the EVM system, EHAC provides an hour amount forecast rather than a ratio index. When preparing budgeted hours, the field management can use EHAC data to establish the reference class of the probable labor costs and contingency factors. Besides the warning signs for budget overruns, EHAC also suggests the potential of how many labor hours (costs) could be saved when workers work at high levels of productivity. For instance, per the EHAC value from week 2, the case project could be completed under budget at 1621 h if the work goes smoothly and the electricians keep up their productivity. This data and its implications can help constructors evaluate and pursue productivity improvement and, therefore, more profitable projects.

Lastly, the authors realized the limitation of this study. The data analysis and conclusions based on the electrical work from one contractor may not be valid for different project scenarios, which introduces the need for more extensive case studies for other construction types in the future research.

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Towards Construction's Digital Future: A Roadmap for Enhancing Data Value

L. Wu and S. AbouRizk

1 Introduction

Taking advantage of the digital revolution of the early twentieth century, many construction organizations have adopted digital technologies to collect and store data in digital formats and assist with various project management functions. Digitization has allowed researchers and practitioners to advance real-time information sharing and collaboration, enhance project assessment and control, and extract untapped insight from data to improve decision-making. Despite benefits gained through digitization, however, the construction industry continues to rely on paper to manage many of its processes and deliverables, including drawings, specifications, and reports [5]. The slow digital transformation of the construction industry has been reported by countless researchers, which have remarked that, unlike its increasingly digitalized customers, the construction industry seems to remain "stuck in the analog era" [14].

Where digitalization has been attempted, research efforts have focused on providing digital solutions to suit a specific dataset collected from a particular project. Numerous decision-support systems, encompassing design, scheduling, material, quality, contract, performance, and safety management, have been developed using this approach. However, the limited scope and insights gleaned from these projects do not extend beyond the specific application. Acting as a catalyst, the COVID-19 pandemic has accelerated the adoption of digital technology across a number of industries by several years [15]. To remain competitive in an increasingly digitalized business and economic environment, the construction sector must go beyond solving company-specific problems. Instead, research must concentrate on solutions that contribute to the transformation of the construction industry-at-large.

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As a step in this direction, this study is proposing a research roadmap aimed at transforming current segmented, raw construction data into timely, reliable, and data-driven decision-support. State-of-the-art digital technologies in literature were reviewed, and prevailing challenges limiting digitalization in construction were identified. Compared with the traditional approach, the proposed roadmap separates the digitalization problem into smaller challenges, abstracts each challenge into a universal construction problem statement, and proposes generalized solutions for each of these challenges. Solutions include (1) developing and generalizing functions to automate and streamline otherwise manual data pre-processing steps, (2) proposing integration of unsupervised learning with supervised learning to automate data parsing and labeling steps, resulting in predictive analytics to maximize the value of insights extracted from large datasets, and (3) proposing two universal methods to fuse subjective and objective data for simulation inputs under repetitive conditions and in situations characterized by high uncertainty. Each step can be applied independently or can be integrated with existing or future digital solutions, as required, allowing the roadmap to grow with and capitalize on the emerging technologies of tomorrow.

2 Data in Construction

2.1 Types of Data

Data are defined as "information, especially facts or numbers, collected to be examined and considered and used to help decision-making, or information in the electronic form that can be stored and used by a computer" [9]. Data are often divided into two categories. The first, hard data, includes "information such as numbers or facts that can be proved" [10] and are often reported as numbers or graphs. The second, soft data, includes "information about things that are difficult to measure such as people's opinions or feelings" [11] that are often associated with uncertainty.

Both hard and soft data exist in construction, and both are required for effective decision-support. The development and implementation of various sensor technologies (e.g. radio frequency identification, global positioning system, laser, and vision-based detection) in construction has drastically increased the speed by which hard data (also referred to as observational data) can be collected [35]. Resulting in large volumes of data that often exceed the capacity of single spreadsheets, hard data are commonly stored in structured, relational databases.

However, construction is characterized by a large amount of uncertainty. Seemingly repetitive operations in construction can differ considerably from one iteration to the next due to external factors such as location, weather, labor skills, morale, and use of technology [26]. Much of the soft data that capture these external factors are exchanged verbally between professionals or stored in unstructured text documents

[4, 8, 20]. As such, a large portion of useful project data, if collected at all, are stored in formats that are not easily indexed or mapped onto standard databases.

2.2 Characteristics of Construction

While the construction sector also struggles with universal digitalization issues, specific characteristics inherent to construction create additional barriers for this industry:

Fragmentation. The lifecycle of a construction project involves a dynamic network of multiple contractors, subcontractors, and specialized trades [22]—each adopting various degrees of technological advancements to suit their operations, capital, and culture [24, 25]. This is especially true for independent subcontractors and suppliers, who have little incentive to invest in advanced technologies for the brief periods during which they are associated with a project [14]. Standardizing the implementation of information technology across a project requires buy-in from all stakeholders, which is extremely challenging in construction.

Complex and Unique. Unlike other industries, construction projects are almost always complex and one-of-a-kind [2, 6, 18]. Many project management processes are applied on a project-by-project basis to fulfill the distinctive contractual requirements of a specific project. The development of universal, generic project management solutions that can be applied to different projects, across multiple project phases, and in a manner that satisfies all project requirements are difficult to achieve.

Transience. Workforce turnover is extremely high in construction at both the project and corporate levels [14]. This results in an organization's reluctance to invest in employee training, which is critical for promoting digitalization. Additionally, a significant amount of information, which is exchanged verbally or via unstructured documents between involved personnel, is never formally captured in a structured format [4, 8]. These data, which often include experts' opinions of the current project conditions and forecasts of future performance, can shed light on factors affecting critical decision-making. Unfortunately, very few of this information is ever captured, thereby leaving the company when the involved individuals depart [20]. The loss of this information can reduce the ability of practitioners and researchers to enhance the performance of future projects.

Remote and Harsh Environments. Unlike manufacturing, which occurs in well-controlled conditions, construction sites are often located in remote and harsh environments [27]. Such conditions present extra challenges for hardware and software development, including limited information technology support and poor telecommunications infrastructure. This can impede quality of the data that are collected, resulting in datasets embedded with missing values, human errors, and outliers.

2.3 Construction Data

As a result, construction data are noisy, both soft and hard, both structured and unstructured, and segmented. The heterogeneous nature of construction data has hindered the development of a standardized digital solution at both the industry and corporate levels. In an attempt to bridge these gaps, many large general contractors have developed information technologies in-house, such as application programming interfaces, databases, and data warehouses. However, this approach creates new challenges, as project data that are collected by different departments end up stored within separate—and often incompatible—data storage sites. These competing systems exist not only within a single organization, but may also hinder collaboration between various project stakeholders.

3 Problem Statement

Considered among the world's least digitized industries by the McKinsey Global Institute [19], the construction industry often places trust in individual experience and expertise over empirics, with very few construction companies employing data analysts or promoting the development of advanced analytics initiatives [13]. Because of this, the transformation of raw, segmented, heterogeneous construction data into informed, reliable decision-support remains one of the foremost challenges limiting the transition of the construction sector from a craft-based field to a data-driven industry. In an attempt to overcome this problem, three specific challenges preventing practitioners from fully exploiting the value of construction data are defined.

3.1 Challenge 1: Heavy Manual Data Manipulation When Pre-processing Raw Construction Data for Project-Level Decision-Support

Existing standalone data management systems result in the segregation of project data into individual data islands that can only support a limited number of data analysis functions and decision-support tasks [23]. Unable to provide a high-level, integrated view, these stand-alone systems often fail to identify connections between various datasets. For instance, a safety database can summarize, report, and visualize safety incidents at various levels of detail throughout the entire project. However, to discover potential correlations between safety indices and various project conditions requires the merging, processing, and cleaning of design, performance, quality, site layout, payroll, and safety data—which are all stored in separate databases.

The level of detail and structures of the data differ drastically between databases, often preventing the data sharing, syncing, and aggregation steps required to extract new insights. Without channels to flow and integrate freely, practitioners must manually manipulate data to enable integration. Moreover, raw construction data often require extensive data pre-processing, such as identifying outliers and data wrangling, to produce robust, predictive, decision-support models [12]. Repetitive and mundane manual manipulation is not only an inefficient use of experts' time but also introduces human error, further lowering the quality of the data.

3.2 Challenge 2: Low Implementation of Machine Learning to Appropriately Deal with the Flood of Available Construction Data

Construction organizations collect a large amount of data that continue to increase as new enabling technologies (i.e. sensors) become available. These large datasets, however, are becoming ever more difficult to analyze by hand. Many construction organizations limit their data analysis efforts to producing summaries of quick, easy, factual information from the large amount of construction data they collect. Because of this, organizations often overlook potentially critical project information hidden within these large datasets, such as connections, correlations, and causal patterns. Rather than maximizing the potential value of data-derived insights, practitioners are increasingly drowning in a flood of a data [16].

3.3 Challenge 3: A Lack of Means for Fusing Heterogeneous Information Derived from Various Sources for Data-Driven Simulation in Real-Time

Data-driven simulation has been widely applied to plan, schedule, and control a variety of construction projects [1]. However, the inability to easily integrate project data in real-time has limited the ability of simulation models to reflect actual project conditions, in turn restricting the widespread use of this tool to the planning stages of construction [16, 20]. The inability to calibrate input models with real-time heterogeneous data remains one of the primary factors contributing to the rigid and static nature of simulation models. The success of a simulation model is highly dependent on accurately modeling its inputs—particularly in construction, where a number of inputs (each imbued with a wide variety of uncertainties) all contribute to the underlying random processes of various activities and tasks.

Modeling inputs as probability distributions, in a process known as stochastic or Monte Carlo simulation, has been widely studied and applied in construction due to its success at incorporating the randomness and various uncertainties inherent to construction activities. However, input probability distributions are often derived using rigid assumptions (e.g. a distribution fitted from historical data or experts' judgments derived from a single source). Solutions capable of fusing actual performance and subjective opinions with original input distributions to achieve real-time updating have been relatively unexplored [3].

4 Proposed Roadmap

This study is proposing a research roadmap (Fig. 1) that is designed to maximize the value of decision-support insights derived from raw construction data. By addressing each of the aforementioned challenges, this research roadmap bridges fragmented construction data with real-time data-driven applications. Application of the roadmap during the development of future decision-support tools is anticipated to increase data usage, to improve the value of data-driven applications, and, ultimately, to promote digital transformation in the construction industry.

Many data-driven applications are limited by their inability to deal with segmented, raw construction data. The first research step, Step 1, addresses this challenge by developing universal solutions to automate common data pre-processing steps, thereby laying a solid foundation for Steps 2 and 3. The roadmap diverges after the first step. One route, Step 2, focuses on the development of data solutions, such as the use of unsupervised learning to reduce the need for manual data parsing in preparation of machine learning-based analytics. The second route, Step 3, centers on the adaptation of methodologies for enabling the calibration of simulation models with real-time input. The research steps are detailed as follows.

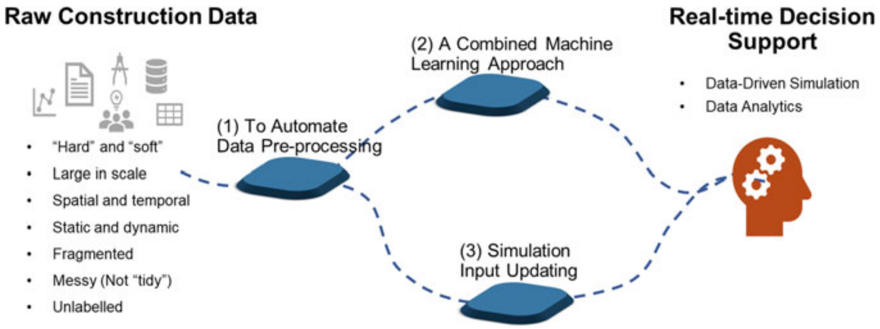

Fig. 1 Research roadmap

4.1 Step 1: Development of Automated Data Integration and Pre-processing Solutions to Increase Information Flow

This step focuses on the development or application of universal, automated data solutions to address labor-intensive data pre-processing steps that are common throughout the construction industry. The solutions will result in the integration and transformation of fragmented, raw data from multiple sources into a format that can be linked with a desired managerial product, data-driven analytics, and/or a simulation model. A key objective of this step is to extract and generalize solutions to common data pre-processing tasks that can be shared and reused in the future. Abstraction of the proposed solutions into public libraries or tools will facilitate the transfer of new, state-of-the-art research throughout the construction industry-at-large.

4.2 Step 2: Application of Machine Learning to Maximize Insight Value Extracted from Data

There are many data-driven, machine learning-based methods or approaches that have the potential to increase the number of insights extracted from the large datasets characteristic of the construction sector. However, application of these methods often require data to not only be merged and pre-processed (as in Step 1), but also to be parsed and labeled to train decision-support tools. Much like data pre-processing, parsing and labeling is a time-consuming task that can benefit from automation.

The second step focuses on adopting unsupervised learning methods to automate the data parsing and labeling processes to streamline the entire machine learning approach. Generalization of this combined unsupervised and supervised learning approach can automate data parsing and labeling, identify and extract critical information from large historical data sets, and form data-driven decision-support tools for future projects.

4.3 Step 3: Enhancing Input Modeling for Dynamic, Data-Driven Simulations in Construction

This step centers on adopting state-of-the-art methods from applied statistics and mathematics to improve the way simulation inputs are modeled in real-time. To achieve real-time updating from as-built data, critical information must be consolidated into the input of data-driven simulation models. This step develops two universal methods generalizable to any given univariate continuous distribution to integrate heterogeneous data from multiple data sources (both subjective and objective) common in construction, thus enabling a new generation of data-driven simulation.

5 Roadmap Application and Discussion

The roadmap was applied to address areas of concern in industrial construction. As is common throughout construction, the industrial construction sector has difficulty integrating fragmented data stores and transforming these data into a format suitable for input into decision-support systems. Application of the roadmap resulted in the development of several proposed solutions. The ability of methods and algorithms, adopted from applied mathematics and statistics, machine learning, data science, and computing science, to address each of the aforementioned challenges were explored. Findings are detailed as follows.

5.1 Step 1: Development of Custom Automated Data Aggregation and Pre-processing Functions

The first step, which serves as a foundation for the two following steps, explores the challenges of low automation in data pre-processing for highly fragmented and non-integrated raw construction data. To address this problem, industrial construction datasets were examined, and two common data pre-processing tasks were abstracted [33]. Two custom functions—both generalized as public *R* libraries—to automate these otherwise labor-intensive tasks were developed. The combination of these two functions effectively processes raw, fragmented, industrial construction data for input into decision-support systems. The two functions are detailed as follows.

5.1.1 Dynamic Programming-Based Longest Common Substring Algorithm

The first function focuses on factors limiting the merging of technical data. Construction data sets are often stored in separate databases with different naming conventions, which complicates data merging. Dynamic programming (DP), first introduced by Richard Bellman [7], has been successfully used to solve problems with overlapping subproblems [21]. A DP-based algorithm can easily identify the longest common substring of any two given strings. Application of this algorithm, therefore, can automate a data merging task that is almost universal in technical construction data sets—specifically, to find common identification or serial numbers (such as a tag ID and drawing numbers) that have been assigned different prefixes and suffixes across various databases [31]. For example, the identification of common substring "-ISO-2222-BFW-" between strings "Project-ISO-2222-BFW-AA" and "Location-ISO-2222-BFW-01". The public *R* library of the automated DP-based longest common substring algorithm function is available from Li et al. [17].

5.1.2 Interval-Based 3D Object Relationship Detection Algorithm

In addition to temporal data, spatial data (such as 3D models) are increasingly being shared and used in the construction phase of a project. Often, 3D design data supplied to industrial contractors are lacking, incomplete, or inaccurate, particularly in the preliminary stages of a project. Quickly identifying relationships between two lists of 3D objects (e.g. two 3D models), requires a time-consuming manual review and calculation. As such, an interval-based 3D object relationship detection algorithm to automate this common spatial data pre-processing task was designed. The algorithm identifies the relationship between two 3D objects given their boundaries on three coordinates (i.e. maxima and minima on x, y, and z coordinates) and systematically evaluates the intersections on each coordinate, thereby identifying relationships between 3D objects. The public *R* library of the automated interval-based 3D object relationship detection algorithm is available from Wu and AbouRizk [29].

5.2 Step 2: Combined Machine Learning Approach to Improve Preliminary Resource Planning

For the second step of the roadmap, a combined unsupervised and supervised machine learning approach to enhance a critical management function in industrial construction—preliminary resource planning—was developed [33]. Industrial construction projects are often completed using the fast-track method, where design and construction phases overlap. Because of a lack of detailed design information, preliminary resource planning in industrial construction has commonly relied on the personal experience of construction professionals. Potential insights that could be gleaned from the analysis of historical project data, therefore, are often never investigated or applied.

The approaches (applied as *R* libraries) described in Step 1 were first used to quickly wrangle three large historical datasets (i.e. BIM, module lifting schedule, and progress database) into a tidy format [28]. Then, unsupervised learning was used to automate data parsing and labeling, resulting in a set of module clusters categorized based on their design. The historical labor requirements for each module cluster were summarized, key resource planning indices were derived, and indices were assigned to each cluster. Then, supervised learning was used to classify and predict the resource requirements for modules in future industrial construction projects. Details of the combined machine learning approach are described in Wu et al. [33].

5.3 *Step 3: Methods for Enabling Real-Time Input Model Calibration for Simulation*

Industrial construction is associated with a relatively large level of uniqueness and uncertainty. As such, the integration of real-time information, as well as subjective input, is particularly important for achieving reliable decision-support results. Current simulation models are developed with rigid parameters and structures that are unable to accommodate actual changes in real-time. As such, their use in industrial construction is often limited to the planning stage.

Although application of Step 1 results in the automatic integration, pre-processing, and conversion of heterogeneous construction data into a tidy format, use of such information as an input for a data-driven simulation model requires additional calibration. In the third research step, input modeling for simulations was studied, limitations commonly preventing the integration of data in real-time were identified, and methods for enabling real-time input model calibration for simulation were investigated. Two numerical-based methods, specifically a Bayesian inference and a geometric average method, were abstracted. The methods are capable of combining subjective and objective data under repetitive conditions and in situations characterized by high uncertainty, respectively.

5.3.1 Numerical-Based Bayesian Inference Method

The first method couples the Markov chain Monte Carlo (MCMC)-based numerical method with Bayesian inference to systematically update any given univariate continuous probability distribution input model of simulations as new observations become available [30]. An illustrative case study was used to demonstrate the generalizability, feasibility, and functionality of the proposed Bayesian inference together with the MCMC-based numerical method for updating simulation input models. The proposed method demonstrates merits of both Bayesian inference, which updates the credible interval of the underlying probability distribution based on real-time data, and the MCMC method, which approximates the target distribution and extends Bayesian inference to cases where analytical solutions do not exist. A detailed description of the methodology is presented in Wu et al. [30].

5.3.2 Numerical-Based Geometric Average Method

The second method couples the MCMC-based numerical method with the weighted geometric averaging method to fuse multi-source data—including both subjective and objective information—to update simulation models in real-time [32]. A Monte Carlo study, as a proof of concept, was developed to test the proposed method against the weighted arithmetic average method and mixture density samples. The generalizability, feasibility, and functionality of the proposed method is demonstrated through an illustrative case study presented in Wu and AbouRizk [32].

5.4 Discussion

Within each research step, the proposed solutions have been abstracted as reusable components, such as generalized data pre-processing functions [33], a generalized machine learning approach [34], and generalized input modeling methods [30, 32]. Their applications to case studies are described in the aforementioned publications. Specifically, the practicality and functionality of research Steps 1 and 2 have been demonstrated in an over billion-dollar industrial construction project located in Alberta, Canada. The algorithms demonstrated in Step 3 have been implemented in *Simphony* [1], a rich modeling environment that is composed of simulation services and a modeling user interface. These reusable components can be adopted as-is to support various construction functions, or can be combined, modified, and extended for greater benefits. These reusable components serve as stepping stones for the future extension, adoption, and modification of the proposed roadmap, enabling the advancement of the digital transformation of the construction industry.

6 Conclusions

6.1 Research Contributions

This research examines current digitalization issues within the construction industry and focuses on the prevailing challenge of maximizing the value extracted from raw construction data through its transformation into insights that can support critical project management decisions. By identifying specific challenges and addressing them individually, this study has paved a research roadmap to promote the digital transformation of the construction industry. Bridging raw construction data to timely and informed decision-support through this research roadmap is anticipated to facilitate adaptation of emerging tools and technologies and to contribute to the digital transformation of the construction industry.

Compared with science and technology, engineering turns methods, algorithms, and ideas into something tangible with a visible impact on society and the daily lives of people. The contributions of this research largely reflect this by responding to current challenges in the construction community: how to fully exploit the value of construction data for informed decision-making. This research identified three challenges preventing information flow and limiting data-driven decision-support systems in construction management. By adapting multi-disciplinary methods, designing domain-specific approaches, and generalizing automated solutions for common tasks, this research removes certain barriers, improves data usage, extends the boundary of existing knowledge, and promotes industrial adoption of data-driven applications, thereby impacting the construction industry and society.

6.2 Limitations and Future Work

The findings and contributions of this research should be applied in consideration of the following limitations.

The proposed roadmap provides effective solutions to bridge raw, non-integrated construction data with data-driven decision-support systems. However, it does not address the root causes nor change the status of the fragmented information systems in the construction industry. Further, due to a lack of appropriate real project data, the application of the entire road map was separated into two demonstration scenarios: Steps 1 and 2 were applied to a case study of a real construction project, and Step 3 was applied to simulated project data. Nevertheless, ongoing research is focused on expanding the roadmap through the integration of various technologies (e.g. optimization, distributed simulation), and the development of a complete decision-support system is underway.

Future research should be carried out in the following areas.

The proposed roadmap should be adapted for different construction practices, focusing on automating manual processes and continuing the transformation of the sector-at-large from a craft-oriented field into a data-driven industry. In this process, specific challenges facing the construction industry should be identified, innovative methods from other disciplines (e.g. applied mathematics, applied statistics, and computer science) should continue to be explored, and solutions for advancing both the academic field and construction practice should be proposed.

Various construction management processes, such as cost forecasting, safety management, stakeholder management, require the application of diverse simulation techniques to accurately model the complex and dynamic construction ecosystem. Methods capable of enhancing the simulation environment by increasing resilience, reliability, and adaptability should be investigated and applied.

A plurality of current construction decision-support systems follow a linear pattern, while real-world decisions follow feedback loops. Future research efforts are needed to (1) identify potential construction feedback loops in actual practice; (2) construct dynamic, data-driven models to simulate these construction feedback loops; (3) understand the implications of changes over time, especially resulting side effects, unexpected factors, and implications, to avoid potential pitfalls in decision-making; and (4) improve mental models of all decision-makers involved to improve construction practices in general.

Finally, artificial intelligence-powered and/or machine learning algorithm-based simulation applications for the construction domain should be explored.

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User Engagement for Sustainable Development: How Can Virtual Reality Help?

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1 Introduction

Early end-user involvement in the design process can lead to significant cost reductions and better product quality [1]. This is while end-user involvement in the housing industry is not widely employed since the housing market is a supplier-oriented one [16]. Zhang et al. [20] mentioned that the lack of enabling technology for active user involvement in design processes hinders this critical requirement. The importance of end-user engagement in the design process is further highlighted when considering the construction industry's impacts on the environment. Today, buildings are responsible for a considerable portion of the total Green-House Gas (GHG) emissions worldwide. In response to the growing concerns about buildings' environmental impacts, the sustainable design of buildings is being encouraged by governments. Around the world, there has been a shift toward green building construction. Designing green buildings requires considering information from multi-disciplinary aspects and calls for the utilization of advanced technologies in the early design stages to evaluate the overall performance of a building. To engage users in this process, various tools are needed to allow collaboration among different stakeholders, regardless of their background.

In recent years, the combination of Virtual Reality (VR) and Building Information Modeling (BIM) has been recognized as a potential solution to such visualization and

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user engagement problems. Approaches towards using BIM for sustainable design have led to a new concept called Green BIM to achieve sustainability and improve building performance [18]. However, the lack of effective visualization is one of the most critical challenges in implementing such an integrated system before construction [14]. Evidence shows that interactive building models improved by game engines have the benefit of enhancing user experience and user communication during various phases in a building project [19].

The application of VR has the potential to improve the collaboration between designers with each other and with clients [11]. This will ensure that everyone affected by design will have early access to its information and influence the final design decisions [2]. Several scholars have assessed the usability of such a system in various aspects of construction such as facility management [15], architectural design [10, 19], and safety and evacuation planning [13, 17].

The advanced visualization capabilities of BIM-VR technologies provide valuable potentials for engaging end-users in the design processes. Since such systems mainly improve model visualization, a topic of interest could be assessing its potentials to select sustainable building materials. The extent of research on user engagement using BIM-VR systems for sustainable design is limited. As a result, this paper investigates the potentials of BIM-VR systems to engage users for sustainable design. Therefore, changing user behavior and user expectations, improving sustainability, or even achieving user-engagement are not the study's objectives. Such studies can only be conducted if the right technologies are used in the right way. This study attempts to take the first steps necessary to answer whether the use of VR is beneficial for promoting sustainable development by engaging end-users in the early design stages; and further how BIM-VR technologies can be used to engage users in a sustainable design process.

2 BIM and Virtual Reality in the Literature

VR enables the engagement of users within a simulated environment and allows understanding user behaviors and expectations in situations that are difficult or even dangerous to realize. For example, VR enables sharing opinions and experiencing different users located far from each other in one virtual environment [4] or analyzing the safety requirements within a building in hazardous situations such as fire incidents [17]. VR has been the subject of numerous studies in the AEC industry in the past two decades. These studies' primary objectives have been design review, user training, 3D coordination, and visualization [9]. The domain of user engagement has also gained interest in recent years. Below, a brief overview of VR applications related to the objectives of this study is conducted. This study aims to design a platform to visualize the information of a building's finishing materials to its end-users.

- **How Can the Proposed System Improved Design Processes?**

VR can help reduce the time needed for design review and modifications by providing detailed design information and improving the communication between different stakeholders [8]. VR allows designers to create their models at the beginning of design stages in a virtual world. As a result, access to spaces that do not yet exist becomes possible [11]. VR environments empower designers to better express and explore their imagination. This can help design processes in many ways. For instance, Rahimian and Ibrahim [12] used VR's visualization capabilities to discover design issues. Chen and Schnabel [3] used mixed reality to explore lost spaces (e.g., missed or undiscovered spaces) in the design process. Besides, VR promotes design processes through improved communication and collaboration.

- **How Can the Proposed System Improve User Engagement?**

Incorporating end-user feedbacks in the design processes is vital for achieving satisfactory results. To achieve this, several studies have attempted to use VR systems to include end-users in design processes. According to Eastman et al. [6], VR will allow users to have a sense of presence and better make evaluations of potential design alternatives in a cost-efficient manner. One of the first studies in this domain is the work of Dunston et al. [5]. They brought the end-users of healthcare organizations (e.g., doctors) in a VR environment to evaluate possible design alternatives for a hospital.

Heydarian et al. [8] mentioned a need to explore VR potentials to involve end-users in the design process. Their study investigated the use of VR technologies to improve the evaluation of design alternatives by engaging end-users in the design process. To this end, they examined whether VR systems can be an adequate representation of physical environments by analyzing user performance in a VR environment as compared to reality. Their study showed that VR was a satisfactory representation of the real environment by adding a sense of presence. They further advanced their work in another study to investigate user behaviors on lighting use [7].

The above work shows that VR provides vast possibilities to engage and assess user preferences and behaviors in different design alternatives. Particularly, VR can improve decision-making in design processes.

2.1 Knowledge Gaps

BIM-VR systems can be considered robust tools for collaboratively engaging users in the design process and visualizing important information. This can be highly valuable in the domain of sustainable design. There can be found a handful of studies that attempted to leverage BIM-VR platforms to encourage sustainable design. However, most of these studies focus on the operational stages, for instance, by trying to understand and changing user behavior through visualizing energy consumption info to them. Research on engaging users for selecting sustainable materials is very limited. Engaging end-users in the material selection stage of design to encourage sustainability can be an interesting study objective with potential values, mainly to increase public knowledge on sustainable development and encourage them to have sustainable perspectives and demands.

3 The Overall Purpose and Framework

The primary purpose of this study is to present a BIM-VR platform that can empower end-users to engage in the process of material selection from the early stages. The scope of the development in this study is limited to the indoor finishing materials. However, the process of utilizing the platform for other building components and elements remains the same, and the proposed method can be easily extended to be used for other parts.

Throwing a large amount of information to a user can confuse and even exhaust the user. This will result in the failure of what the platform is trying to achieve. Thus, the proposed platform represents cost (purchase and installation), energy performance, and embedded GHG emissions to users in a virtual environment. Other information, such as geometrical info, will also be represented. This way, users will know how each design scenario will look and how much it will cost and impact the environment.

The proposed platform allows users to walk through the building and select different model elements (e.g., walls). Once an element is selected, the system automatically detects all the possible design scenarios for the element and represents them to the user (e.g., a wall can be covered with wood or Gypsum). Once the user selects a design scenario, the system updates the model to visualize to the user how the scenario looks like and, at the same time, represents the design information to the user. The development of such a platform requires a number of technologies, including Building Information Modeling (BIM), Virtual Reality (VR), Database Management systems (DBMS), Application Programming Interface (API), and Energy Analysis (EA) tools. Figure 1 shows the overall framework used in this study to integrate these technologies.

4 Developing the GUI

A Graphical User Interface (GUI) is used to allow users to walk through the model and test different design scenarios. Figure 2 shows how the algorithmic performance of the proposed GUI in this study. First, the user selects an element, and based on the element's ID, the platform identifies the possible design scenarios for the element and asks the user to choose a scenario. Once the user selects a scenario, the model is updated to implement the design scenario in the virtual environment so that the user can have a visual understanding of what the scenario would look like. Next, the platform accesses the information of the design scenario and represents them to the user in three different categories of material information (what materials and what quantities), energy information (e.g., thermal properties), and energy analysis results

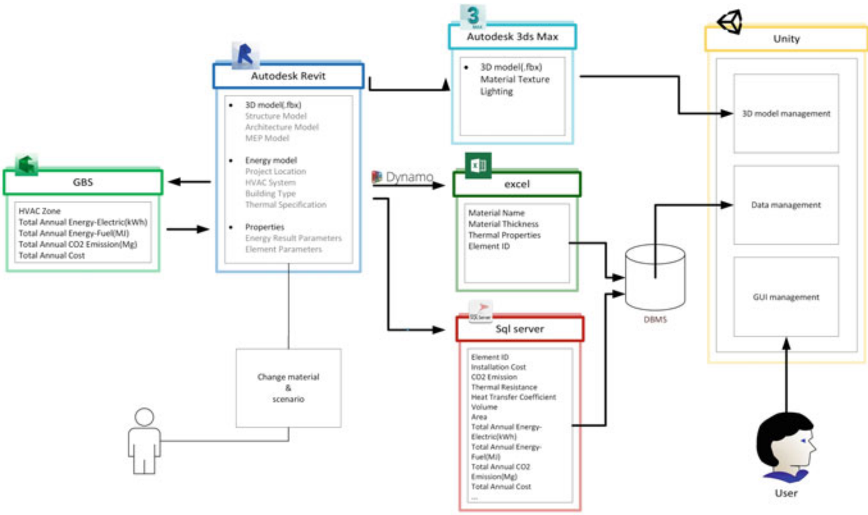

Fig. 1 The overall data flow from BIM to VR

(retrieved from GBS). In general, any information about the element can be queried and shown in the GUI.

5 Test Case Design

The purpose of this section is to evaluate the performance of the proposed system. The case study was the construction of a twelve-story residential building located in Tehran, Iran. The BIM model, depicted in Fig. 3, was used to conduct energy analysis with GBS. Since the energy analysis details are outside the scope of this research, they will not be discussed.

5.1 System Development

The GUI consists of two main components. The first component appears whenever a user selects a building element, as shown in Fig. 4. This component shows the possible scenarios that are considered by the designers as possible design options for that element. The second component appears after the user selects a scenario. The purpose of this component is to provide design and analysis information for the user-selected scenario.

In this project, two possible scenarios for designing the interior walls of the building are considered. In the first scenario, the interior walls of the halls are covered

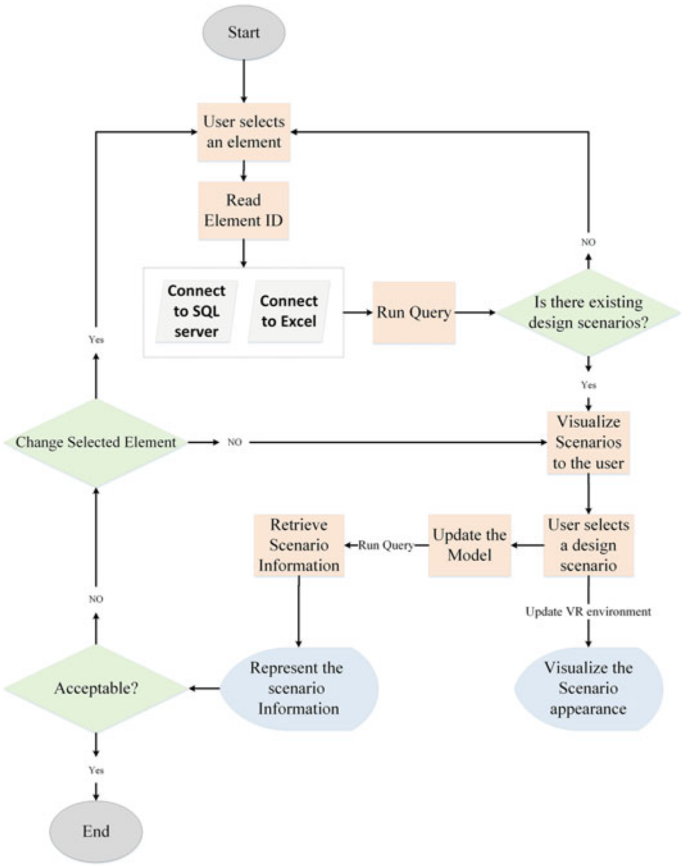

Fig. 2 GUI algorithm

by Gypsum, and in the second scenario, the walls are covered by wooden panels. After design scenarios are determined and energy analysis is conducted, design information and analysis results are stored in the databases connected to the VR environment. The system can show users each scenario in terms of visual appearance, energy performance, and cost. This will allow the users to have a broader understanding of how a building can be designed sustainably rather than just considering options based on aesthetics and costs.

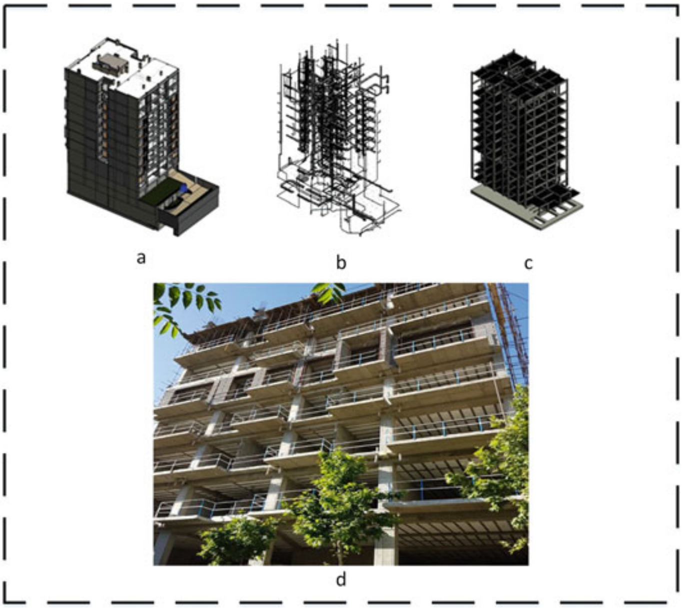

Fig. 3 Case study building and models

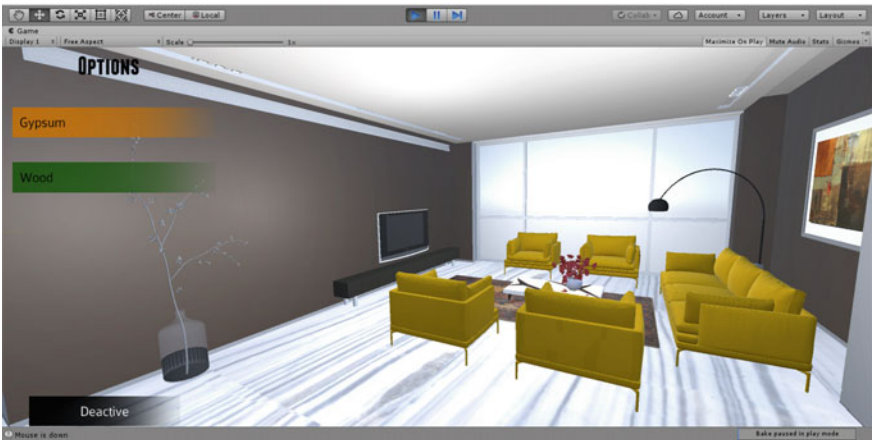

Fig. 4 The GUI developed for the case study

5.2 Testing

The ultimate value of the developed system is in engaging customers in the design process of the building to increase its overall sustainability. The following three sub-elements can be considered for testing and evaluation, (1) the technical performance of the system (e.g., software interoperability and data flow), (2) whether the system succeeds in engaging users in the design process and educating them, and (3) whether the system succeeds to improve the overall sustainability of design.

The first sub-element can be validated in a focus group of experts and professionals who put the system into use and assess its performance. This study evaluates the second sub-element by asking a number of interested customers of the residential building to work with the system and give their feedback. However, validating the third element is not possible in this study. This is mainly because the system's possible impacts should be first evaluated to see whether it can attract end-users' interest. Once the system is evaluated and fine-tuned to become capable enough for engaging users in the design process, the designers can start adding different design scenarios and asking its potential customers to use the system. However, without this evaluation, such a wide-scale analysis is likely to cause more harm than good. For instance, if lots of effort is put into designing different design scenarios, but customers would not find the system interesting, understandable, or even usable (bugs), it would both harm the reputation of the company and waste all the time dedicated to preparing design scenarios. As a result, in this study, the evaluation is conducted qualitatively rather than quantitatively. Future studies will improve the system based on this study's results and evaluate it in a wide-scale quantitative analysis.

Technical analysis was conducted by assessing (1) whether the system visualizes each design scenario correctly (e.g., walls are covered with Gypsum or wood panels) and (2) whether the information represented for each design scenario is correct. After a few iterations (in which system bugs were identified), the system was finalized for end-users. After the technical performance of the system was verified, a showroom was held to introduce the building to potential customers and real estate agents using the developed system. Figure 5 shows the environment in which the showroom was held and how the audience participated in the process. Through asking questions, participants were engaged in an open discussion to present their views. The most engaging participants, including two customers (who later purchased a unit) and one real estate agent, were interviewed individually to give them a better chance to provide their feedback. General feedback about the system was positive. The followings are critical points concluded from the interviews:

- End-users indicated that their primary concern is the comfort level of the building environment. Their perception of comfort was primarily the light level in the unit, high-quality facilities (for heating and cooling, water, and electricity), and view of the outdoor environment.
- Building customers indicated that the usage of VR technology for presenting the building gave them a sense of trust regarding the overall quality of the building.
- Customers indicated that using the proposed system in this study led them to believe that the company values their opinions and that they can trust the company with the operation and management of the building.
- From the perspective of investors and real estate agents, today, customers are constantly looking for improvement, and improvement demands difference. Exposing users to high-level technologies gives them a sense of confidence that

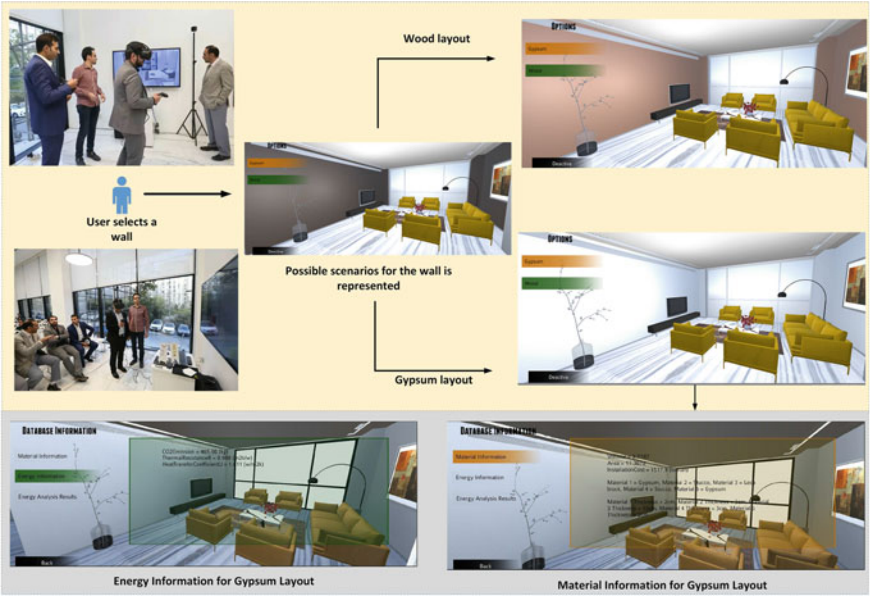

Fig. 5 Presenting and testing the developed system

the building is distinguished in terms of technical design and construction. This has positive marketing impacts for investors.

6 Limitations

This study is limited in terms of the extent of system application. Currently, the system was only designed for wall materials and needs to be extended to include other elements as well. Moreover, the current system can be extended to employ advanced studies for capturing participant feedback. However, the most notable limitation of the study is the system evaluation process. The current approach uses a simple qualitative review over user perceptions to evaluate the proposed system. This is mainly because the work is more of an exploratory analysis rather than an evidence-based one. This study aims to explore how we should approach user engagement using BIM-VR platforms to achieve more sustainable design and possible benefits that it can have. Although, quantitative analysis is not a suitable/feasible approach for such studies (given that it would be difficult to collect adequate sample size), more in-depth analysis is required to reach depth and breadth regarding the results in future works.

7 Conclusion

This study acknowledges the importance of engaging end-users in design processes to achieve a sustainable design. To this end, this paper focused on the development of a BIM-VR platform to engage end-users in the selection of wall finishing materials. The proposed platform was then utilized in a real-life case study to evaluate its performance both in technical terms and its effectiveness. The technical performance of the tool was evaluated and improved in a focus group of 4 experts. The effectiveness of the tool was performed by presenting the tool in a showroom. It was mainly a qualitative analysis because the primary purpose was simply to learn what information should be visualized and the way it should be visualized. This is mainly because the authors believe that before advancing towards studying the impacts and benefits of engaging users in the design process, we should first find the right way to do so. It was also discovered that valuing end-users' expectations when designing a building gives them a sense of trust, which will result in more successful stakeholder interactions. This can be a motivation for construction companies to invest in user-engaging technologies.

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An Examination of Quality Management System Implementation in Egyptian Contracting Companies

N. Elsokhn and A. Samer Ezeldin

1 Introduction

The construction industry is a leading sector in the Egyptian economy, and it has been exposed to continuous growth since the 1980s. Elghamrawy and Shibayama [8] indicated that in 2001–2002, the construction industry's gross domestic product share is \$3.84 billion, representing 4.7% of the total gross domestic product. On the other hand, the ministry of planning indicated that in 2019–2020, the industry's gross domestic product share is \$23.75 billion, representing 6.7% of the total gross domestic product. While the construction investments reached \$2.6 billion, representing 8.7% of Egypt's total investment. These figures represent the remarkable growth experienced by the construction industry, which contributes to the provision of job opportunities, domestic investment, and national development as well. On the other hand, the construction industry has complex and dynamic nature due to various participants' involvement with different perspectives and interests. Additionally, it is characterized by confrontational and adversarial nature with time and money governing [3, 12]. Therefore, Contractors only seek to increase their profit by delivering the minimum requirements of quality and rarely consider quality improvements, resulting in poor quality, performance, and lack of customer satisfaction. According to the competitive markets and globalization nowadays, organizations' performance cannot be measured only using quantifiable measures such as cost, schedule, profit, defect rates, productivity, and inventory turnover. Qualitative measures such as customer satisfaction, innovation, process improvement, and skill development must be considered while evaluating the organization's performance [11].

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A paradigm shift is required to embrace quality and make it the new business philosophy of construction organizations to improve their image and regain their competitive advantage [9]. Managing quality for a construction organization is as essential as operational and managerial processes. Quality management emphasizes the organization's fitness and assists it in offering high-quality service, sustaining its competitiveness, and meeting customers' satisfaction requirements. In order to gain control of quality management, many organizations invest in adopting a quality management system (QMS). The American society of quality has defined QMS as "a formalized system that documents processes, procedures, and responsibilities for achieving quality policies and objectives. A QMS helps coordinate and direct an organization's activities to meet customer and regulatory requirements and improve its effectiveness and efficiency continuously". Moreover, Rocha-Lona et al. [21] defined QMS as a set of elements forming an integrated business approach that demonstrates the organization's implementation of quality management models, methods, and tools. These elements are human capital, processes, management models, methods and tools, business strategy, and information technology. Quality problems in the construction industry can be resolved by implementing QMS as proper QMS implementation ensures the consistent and reliable management of the client's requirements and satisfaction. Besides, it fulfils the organization's requirements efficiently as it creates uniformity, avoid problem reoccurrence by providing the organization the opportunity to restructure and modernize its management [4, 13].

Contractors have misconceptions about deploying QMS; they believe that it adds unnecessary costs and not suitable for any organization. However, the implementation of QMS minimizes the costs associated with non-conformance to quality, such as the cost of rework, waste, errors, cost overruns, and schedule delays [8, 19]. Moreover, QMS can be designed to suit any entity regardless of its business nature or size, as long as it is aligned with its business strategy [17]. The established system's complexity can vary from one organization to another, it can be a simple inspection and testing system or a fully comprehensive system [10]. Successful QMS tools that showed potential in the manufacturing industry are Total Quality Management (TQM), ISO, Six Sigma, Lean and Business Process Reengineering (BPR), Business Excellence Models (BEMs), and others [10].

The construction industry is lagging behind other industries in terms of the successful adoption of QMSs. QMS has been widely explored from the context of different industries and countries. However, a few studies addressed it from the standpoint of a developing country and its construction industry. As a result, Egyptian organizations have been implementing universal quality philosophies and methods that cannot be effectively applied without suitable adaptation to Egypt's cultural, economic, social, and technological background. Moreover, the lack of awareness towards QMS implementation barriers and lack of acceptance of QMS benefits among stakeholders have negatively impacted the contracting companies. In conclusion, construction companies require support and guidance for adopting QMS. Towards a better understanding of QMS and examining the perception of Egyptian contracting companies regarding QMS implementation, three objectives have to be accomplished:

1. Identify and evaluate the barriers encountered by contractors during implementation.
2. Identify and evaluate the benefits received by contractors after implementation
3. Identify and evaluate the critical success factors for implementation

In this paper, the first part discusses the extant literature associated with the concept of QMS in the construction industry and the barriers that impede the adoption of QMS, along with the benefits and CSFs for successful QMS implementation. The second part describes the methodology utilized and the questionnaire carried out to fulfil the study objective. The results and the analysis of the questionnaire are presented in the third part. Finally, the last part highlights the conclusion and recommendations.

2 Literature Review

In order to achieve effective QMS implementation, identifying the barriers encountered by different organizations during QMS implementation may help understand their severity and act proactively to solve any problem. Ahmed et al. [1] categorized barriers that affect QMS adoption into six categories according to their origin: managerial, organizational, financial, cultural, educational, or auditing. A study conducted on the Indian industries suggested that the main barrier in implementing QMS is the lack of benchmarking, employee resistance, and inadequate resources [24]. Rogala [22] approved that inadequate resources may affect the successful implementation of QMS, in addition to the staff's insufficient involvement. On the other hand, employees' resistance to change and attitude towards quality were the top-ranked barriers in the Indian service industries such as healthcare, information and technology, banking, and hospitality industries [25].

Aichouni et al. [2] concluded that awarding contracts to the lowest bidder is the main barrier affecting QMS implementation in the Saudi construction industry, along with the lack of an effective team and skilled workforce. According to 208 contractors surveyed in the U.S., similar results were obtained [12]. In the Turkish construction industry, the prolonged implementation process, increased expenses, and unacceptable critics are the top barriers that confronted companies [26]. However, out of 18 potential barriers, lack of top management commitment, support, and leadership were the top three scored barriers by the Turkish contractors. According to the survey, top management's apathy and disregarding QMS implementation value may lead to its failure [20]. Elbassuni [7] investigated the barriers faced by Egyptian construction companies that occurred during implementation. The results revealed that resistance to change, lack of management commitment, and the unclear benefits for employees are the three most significant barriers. These barriers are consistent with the results obtained by manufacturing firms in Egypt [15]. On the other hand, managers in the Indonesian construction companies agreed that the misconception about QMS implementation purpose and the lack of reward system are the two significant barriers they face [27].

On the other hand, benefits differ from one organization to another based on their quality objectives and level of commitment. Samsudin et al. [23] indicated that if a process, people, and documentation were appropriately planned, that would improve the organizations' image and satisfy all the stakeholders. UAE companies agreed that QMS implementation benefits their internal operations, as the four most important benefits are process and procedures improvement, employees' quality awareness, product or service quality improvement, and better customer service [28]. Similarly, Turk [26] specified the benefits that return to the Turkish contractors from QMS application are improved image, improved processes and procedures, improved communication internally and externally, and better definition of responsibilities. Nevertheless, they claimed that the application did not affect their business volume or market share. Another survey delivered to the Turkish contractors by Polat et al. [20] indicated different acquired benefits: customer satisfaction and confidence, repeated customers, and reduced rework and nonconformities. These benefits conform to the Malaysian construction industry [23]. Othman and Rashed [18] claimed that implementation improved the contractors' performance, image, and competitive advantage. Improvements in construction processes and employee satisfaction are considered more significant, while profit, savings, and customer satisfaction less significant [2]. Quality managers recognized nine benefits for QMS implementation in the Egyptian construction companies, the most important benefits are the improvement of records and the retrieval of information efficiently for litigation and claims, increased customer satisfaction, and improvement of traceability of quality problems [7].

Furthermore, CSFs are believed to be several factors that, if aligned together, will assist the organization to accomplish successful QMS implementation and evaluate the system applied. Despite the significance of identifying the factors, there is no agreed universal list of CSFs in the construction industry. Therefore, each study seeks to specify the factors according to their context, scope, and purpose [1, 21]. Kumar and Sharma [14] identified 20 CSF from the literature and introduced them to three companies. They concluded that the importance of CSFs is different between each company. Failing to identify and recognise CSFs is considered an implementation barrier as the organization may struggle to implement QMS or enhance its performance [10]. Chin and Choi [5] indicated that the most significant CSFs in the Hong Kong construction industry are top management commitment, strategic decision-making, and effective implementation of decisions. Top management commitment encourages all the organization's commitment to quality and continuous improvement, which resulted in improved performance, reduced resistance to change, enhanced problem-solving, effective human resources management, and increased competitive advantage.

Magd [15] presented eleven factors for Egypt's manufacturing industry, the respondents evaluated them and suggested top management commitment, a well-structured system of procedures, and the organization's internal auditors are the main CSFs. Ahmed et al. [1] identified twelve CSF and agreed that top management commitment is the top one, followed by leadership support and management feedback. Aichouni et al. [2] mentioned that the Saudi construction companies perceive employee satisfaction, customer satisfaction, teamwork and people involvement, leadership, and process improvement as success factors. According to Othman and Rashed [18], the highest factor affecting the construction project's success is the skilled work force, then training and education and project performance.

3 Research Methodology

According to the reviewed research work relevant to QMS implementation and factors affecting its effectiveness, a questionnaire was developed to investigate QMS implementation in the Egyptian contracting companies. The questionnaire method is used as a quantitative approach in order to gather holistic knowledge from various organizations to determine the current status of QMS implementation and measure each factor's significance within the Egyptian contracting companies. It comprises 17 closed or scale questions divided into four parts: personal information, contractor's information, quality management system status, and perception of contractors on QMS implementation. For validation, pilot test questionnaires were carried out to ensure the clarity and accuracy of all the statements and eliminate any mistakes or errors. Received comments and feedback were taken into consideration.

The questionnaire was addressed to top and middle-level managers and quality management representatives within contracting companies, as they influence quality improvement within the company and QMS implementation. Each organization is represented by only one response. A sample of 55 contracting companies received the questionnaire, 36 responses returned, and eight responses were excluded from the analysis due to repetition, non-qualified respondents, or inconsistent responses. Therefore, the total valid responses are 28, which corresponds to a response rate of 50.9%, which is almost similar to the sample size of different studies [6, 7]. The quantitative data collected were statistically analysed using the Statistical Package for Social Sciences (SPSS).

4 Findings and Discussion

Table 1 summarizes the respondents' profile as the respondents' qualifications ranged from Bachelor to Ph.D., their job title and years of experience also varied. It is noted that the majority of the respondent's have only a bachelor's degree, and almost half of them is a general manager or a quality manager. Besides, most of the respondents have a long working experience.

On the other hand, Table 2 illustrates the contractors' characteristics, including the type of works, grade level, type of ownership, years of establishment, and company size. Grade level refers to the Egyptian Federation for construction and building contractor's classification for contracting companies. It classifies contractors into seven grades, where grade one is the highest, while grade seven is the lowest based

Table 1 Respondent's profile

Respondent's profile	Frequency	Percentage
1. Education level		
PhD	2	7.1
Master	11	39.3
Bachelor	15	53.6
2. Position of the respondent		
Chairman	1	3.6
General manager	8	28.6
Quality manager	6	21.4
Department manager	4	14.3
Project manager	6	21.4
Senior engineer	3	10.7
3. Number of years of experience		
Less than 5 years	2	7.1
5–10 years	6	21.4
11–15 years	9	32.1
16–20 years	4	14.3
More than 20 years	7	25.0

on paid capital, years of establishment, the number of employees, owned equipment, and the highest value of project performed. The sampled companies' primary projects sector is building works with 47.1%. The results show that 60.7% of the sample are grade one companies, 3.6% are grade two and three, 25% are grade four and five, and 10.7% are grade six and seven. In addition, the companies are categorized according to types of ownership; 50% of the sampled companies are family owned. According to the number of years of establishment, most companies are established for more than 20 years, while employee size classification illustrates that 75% are considered large organizations. The respondents' and the companies' demographic information represent a wide range of experienced professionals and indicate their qualifications for this study purpose.

In order to explore the QMS status among contractors in Egypt, quality department existence, QMS application, and certification are examined. Out of 28 respondents, 16 companies have a quality department, while five companies are in the process of initiating it. The responses revealed that companies integrate different tools of QMS in order to obtain the best results; 18.4% implement TQM, 36.8% implement ISO, 28.9% implement an in-house quality management system, and 15.8% do not implement any QMS. Table 3 indicates the QMS status summary; the results presented are promising as the majority of the sample is aware of the quality significance and seeks QMS application and certification.

Table 2 Characteristics of the contractor

Characteristics of the contractor	Frequency	Percentage
1. Main projects sector		
Building works	16	47.1
Infrastructural works	5	14.7
Electro-mechanical works	9	26.5
All	4	11.8
2.Grade level		
Grade 1	17	60.7
Grade 2,3	1	3.6
Grade 4,5	7	25.0
Grade 6,7	3	10.7
3. Type of ownership		
Sole propriety	7	25.0
Family owned	14	50.0
Shareholding	1	3.6
Multinational company	6	21.4
4. Number of years of establishment		
Less than 5	2	7.1
6–10 years	4	14.3
11–20 years	7	25.0
More than 20 years	15	53.6
5. Size of the organization		
Less than 50 employees	3	10.7
51–100 employees	4	14.3
101–250 employees	6	21.4
251–500 employees	3	10.7
More than 500 employees	12	42.9

The respondents were required to rate the barriers, benefits, and CSFs using a five-point Likert rating scale (1 = strongly disagree, 5 = strongly agree). A descriptive analysis, along with T-test statistical analysis techniques, has been used in the evaluation. Then, the factors are ranked in decreasing order by their *t*-test value into determine the significance. The confidence level is set at 95%, thus $\alpha = 0.05$. A reliability test is performed to measure the internal consistency and homogeneity of elements of the same group. Cronbach's Coefficient alpha is the indicator of a measurement scale's uniformity for questionnaires with rating scales; its value should be within a range of 0.70–1.00 [2]. The Cronbach alpha values for QMS implementation barriers equal to 0.812, benefits equal to 0.892, and CSFs equal to 0.837. These values are acceptable and indicate the high reliability and consistency of the questionnaire's scale.

Table 3 QMS status summary

Quality management system status	Frequency	Percentage
1. Quality department existence		
Yes	16	57.1
No	7	25.0
In process	5	17.9
2. QMS applied		
Total quality management (TQM)	7	18.4
International organization for standardization (ISO)	14	36.8
In-house quality management system	11	28.9
None	6	15.8
3. Certification		
ISO 9000:2000 quality management system	3	6.1
ISO 9000:2008 quality management system	4	8.2
ISO 9000:2015 quality management system	10	20.4
ISO 45001:2018 occupational health and safety management system	11	22.4
ISO 14001:2015 environmental management system	8	16.3
None	13	26.5

Table 4 presents the mean, standard deviation, *t*-values, and *p*-values results for the identified barriers. Out of 18 potential barriers five barriers were neglected due to their insignificance at a 95% confidence level: the lack of well-trained internal auditors, difficulty controlling the construction process, insufficient organizational resources, time-consuming, and increase of paperwork and documentation. The implementation barriers are listed in decreasing order by *t*-value. Lack of a well-designed reward system and the high cost of developing and utilizing a quality management system are the lowest significant barriers. While, the top four significant barriers are, respectively:

1. Resistance to change.
2. Ineffective communication and feedback between departments.
3. Lack of top management commitment.
4. Poor quality action plan.

As shown in Table 5, 18 implementation benefits have been identified and evaluated. According to the t-test and mean values, improving customer satisfaction appears to be the leading benefit for implementing QMS in Egyptian contracting companies, followed by improving the company's image. On the other hand, the lowest perceived benefits in this study were profitability improvement and incidents rejections and complaints.

This study presented 11 CSF for contractor's evaluation; the results are showed in Table 6. The most important factors are:

1. Top management commitment and leadership

Table 4 QMS implementation barriers for contractors in Egypt

QMS implementation barriers	Mean	SD	*t*-value	*p*-value
Resistance to change	4.50	0.793	10.003	0.000
Ineffective communication and feedback between departments	4.14	0.932	6.492	0.000
Lack of top management commitment	4.21	0.995	6.460	0.000
Poor quality action plan	4.00	0.903	5.862	0.000
Difficulties in understanding the quality system	3.89	0.875	5.399	0.000
Lack of quality awareness	4.07	1.152	4.920	0.000
Awarding of contracts to the lowest bidder	3.82	1.090	3.986	0.000
Lack of qualified workforce	3.75	1.041	3.813	0.001
Improper organizational structure	3.68	1.124	3.195	0.004
Difficulties in controlling subcontractors and supplier	3.71	1.213	3.116	0.004
Lack of continuous improvement culture	3.75	1.295	3.066	0.005
Lack of a well-designed reward system	3.50	1.106	2.393	0.024
High cost of developing and utilizing a QMS	3.54	1.290	2.197	0.037
Lack of well trained and experienced internal auditors	3.43	1.136	1.996	0.056*
Difficulty in controlling the construction process	3.46	1.232	1.995	0.056*
Insufficient organizational resources (financial, human)	3.43	1.230	1.844	0.076*
Time consuming	3.29	1.272	1.188	0.245*
Increases in paperwork and documentation	3.18	1.219	0.775	0.445*

* p-value < 0.05, insignificant at a 95% confidence level

2. Attitude to change.
3. Continuous improvement

    And the least important are:

4. Involvement of suppliers and subcontractors
5. A well-structured system of procedures and processes
6. Employees empowerment

5 Conclusion

QMS in the construction industry is often implemented to ensure that companies make sufficient effort to achieve clients' required quality levels. Meeting customer requirements and expectations are essential to any business's continuity and growth and attaining these quality levels ensures long-term competitiveness. This paper investigated the perceptions of Egyptian contracting companies toward QMS implementation. Therefore, questionnaires were sent to 55 contracting companies throughout Egypt, a total of 28 valid questionnaires were returned, representing a response rate of 50.9%.

Table 5 QMS implementation benefits for contractors in Egypt

QMS implementation benefits	Mean	SD	*t*-value	*p*-value
Improves customer satisfaction and confidence	4.64	0.731	11.892	0.000
Improves the image of the company	4.61	0.737	11.534	0.000
Reducing inefficiencies and waste	4.21	0.686	9.363	0.000
Improves service quality	4.43	0.879	8.601	0.000
Increases competitive advantage	4.18	0.905	6.892	0.000
Improves processes and procedures	4.14	0.932	6.492	0.000
Enhances continuous improvement	4.11	0.916	6.392	0.000
Gaining entry in new markets	4.21	1.031	6.231	0.000
Improves budget and schedule performance	4.00	0.903	5.862	0.000
Reduces rework	4.04	0.999	5.484	0.000
Effective promotional and marketing tool	3.96	0.999	5.106	0.000
Improves productivity	3.82	0.905	4.804	0.000
Improves employee satisfaction	3.89	0.994	4.753	0.000
Improves communication between all project stakeholders	3.79	0.917	4.533	0.000
Improves communication with suppliers and subcontractor	3.82	1.090	3.986	0.000
Increases market share	3.93	1.245	3.946	0.001
Improves profitability	3.64	0.870	3.911	0.001
Incidents rejections and complaints	3.68	1.249	2.875	0.008

Table 6 QMS implementation CSFs for contractors in Egypt

QMS implementation CSFs	Mean	SD	*t*-value	*p*-value
Top management commitment and leadership	4.54	0.637	12.752	0.000
Attitude to change	4.18	0.612	10.193	0.000
Continuous improvement	4.11	0.629	9.316	0.000
Effective communication within the organization	4.18	0.723	8.628	0.000
Education and training	4.21	0.787	8.167	0.000
Use of information and communication technology	4.07	0.858	6.611	0.000
Customer satisfaction	4.11	0.916	6.392	0.000
Employee motivation and commitment	4.04	0.881	6.220	0.000
Employees empowerment	3.93	0.813	6.042	0.000
A well-structured system of procedures and processes	4.07	0.979	5.793	0.000
Involvement of suppliers and subcontractors	3.54	1.071	2.647	0.013

This paper analysed the top and middle-level managers' and quality managers' views concerning implementing QMS in the Egyptian contracting companies, focusing on implementation barriers, benefits, and CSFs. The main barrier was found to be resistance to change, while the top perceived benefit is improving customer satisfaction. Contractors can get over this barrier by offering training programs to their employees in quality, QMS tools, implementation, and anticipated benefits. On the other hand, the findings suggested that top management commitment and leadership is the most critical factor for a successful implementation, as top management is accountable for developing proper QMS, providing adequate resources, and leading the implementation process by educating and motivating the employees involved.

This paper contributes to providing a better understanding of QMS implementation in contracting companies and increasing the awareness among construction professionals for encouraging the growth and development of the Egyptian construction industry. Moreover, the questionnaire results provide a strong basis for future research to develop a framework for quality implementation to facilitate the successful implementation of QMS and promote quality management practices improvement in Egypt's contracting companies.

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Association of BIM-Related Contract Language and BIM Use on Construction Projects

A. Celoza, D. de Oliveira, and F. Leite

1 Introduction

Building information modeling (BIM) in the architectural, engineering, and construction (AEC) industry is transforming how construction projects are delivered. BIM is a "digital representation of physical and functional characteristics of a facility" and is a shared information system [15]. BIM can provide benefit throughout a project's lifecycle by enabling uses such as design coordination, 4D scheduling, quantity takeoffs, and facility management. Furthermore, BIM use has been linked to improved project performance with respect to delivery speed [11]. As BIM has the potential to improve project performance in the AEC industry, there is a need to understand how to improve BIM adoption among project stakeholders. BIM is a common information repository for all project stakeholders. Hence, the more participation and buy-in of stakeholders in this system could lead to a better information management and overall project performance. Traditionally, contracts have been used to define expectations and requirements for stakeholders. Current research in BIM and contracts focuses on identifying the potential areas of dispute and risk [5, 6] and there is little focus on how contracts can impact stakeholder use of this technology at the project level. To this end, researchers focused on the relationship between contract requirements and BIM use. The objective of this study was to evaluate the association between BIM-related

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contract requirements and BIM use on construction projects. Researchers specifically evaluated the use of BIM by key stakeholders (architect/engineer, contractor, subcontractor) and the use of a BIM execution plan (BEP).

2 Background

2.1 Literature Review

Researchers conducted a literature review focused on the implementation of BIM and BEPs, and the relationship between contracts and BIM. When reviewing literature related to BIM and BEPs, researchers focused on identifying benefits to stakeholders and the project as a whole to make the case for BIM adoption by project stakeholders. When reviewing previous research related to contracts, researchers wanted to understand the potential BIM-related contractual challenges and how contracts currently address BIM. Overall, researchers wanted to understand BIM's impact on construction projects and how contracts could impact BIM adoption and implementation on the project level.

2.1.1 BIM Implementation

BIM is a "shared knowledge resource for information about a facility" [15] and can be used as a collaborative tool throughout a project's lifecycle. One of the major benefits of BIM is that it can be used as a common source of information, decreasing the need to manually transfer or recreate information in stakeholders' respective systems. For this benefit to be achieved, relevant project information needs to be captured in a single repository, which requires participation of major stakeholders throughout the project's lifecycle. With BIM implemented on a project, there are numerous applications that stakeholders can take advantage of, including design coordination, photorealistic renderings to communicate with stakeholders, contractor coordination, and schedule management [14]. These applications can provide benefit for specific stakeholders in their specific project scope; for example, BIM can be used by contractors and subcontractors for coordination among construction trades to avoid conflicts during field installation and minimize trade stacking, or BIM can be used by designers to improve collaboration among a distributed design team. In addition to benefits for specific stakeholders or project phases, BIM can also improve a project's overall performance. Franz and Messner [11] evaluated BIM uses' effects on project performance. They analyzed over 200 projects and found a significant positive relationship between BIM use and speed of delivery when controlling for project complexity. Overall, BIM has the potential to improve construction projects at both the stakeholder level and the overall project level.

2.1.2 BEP Implementation

A BIM execution plan is used to define BIM goals and uses, develop project specific information exchanges, and define BIM processes [9]. This process is a result of a collaborative effort that represents stakeholders' specific goals and requirements for BIM use throughout a project's lifecycle. Having these procedures documented is critical; researchers have identified a documented BEP as a critical success factor in construction projects implementing BIM [7]. Furthermore, research into the relationship between BIM use and BEP creation indicates that participating in a BEP's creation was a predictor of BIM use [11]. When stakeholders have the opportunity to participate in BIM execution planning, they are given the opportunity to discuss their shared and organizational goals, as well as the processes that are required to achieve those goals, which can ultimately lead to project success. This suggests the importance of stakeholder buy-in to BIM, including its uses and the overall process required to implement it at the project level.

2.1.3 Contracts and BIM

Previous research on contracts and BIM address areas of legal and technical risk, as well as, project performance. Assaad et al. [6] evaluated standard agreements in the United States (US), such as American Institute of Architects (AIA) agreements and ConsensusDocs, with respect to how they address BIM risks and potential issues arising from the implementation of BIM. They identified data management and collaboration, management of information discrepancies, and indemnity as areas of contractual concern. Arshad et al. [5] identified risks related to BIM in design/bid/build projects and proposed mitigation strategies. These risks include intellectual property, professional liability, and challenges with model management. Many of the proposed strategies to mitigate these risks include the use of additional contract language addressing specific risks and defining a BIM process, often using a contractually obligated BEP [5, 6]. Another study, conducted by Hamdi and Leite [12], identified legal challenges when implementing BIM through the use of expert interviews. Their study identified numerous challenges, including the need for all stakeholders to be involved in BIM and that there are gaps in current contracting strategies with respect to BIM. Additionally, the importance of interfaces between design and construction, and construction and operations were highlighted, underscoring the need for consistent BIM requirements and expectations across a project's lifecycle. This focus on interfaces highlights the importance of key stakeholder participation in BIM throughout the project. Additionally, a study evaluated the relationship between contractual BIM requirements and project cost performance and found that contractually requiring the contractor and subcontractor to use BIM were factors related to project cost success [8]. This existing research develops an understanding of BIM risks and contractual remedies, as well as, the impact of BIM-related contractual language on project performance, however, there is a lack of understanding on how project contracts can impact BIM use by project stakeholders.

2.2 Motivating Case

With numerous challenges identified in literature, it's important to understand how these challenges occur in practice. Issues have arisen regarding inconsistent BIM requirements among stakeholders. One notable case is *North American Mechanical, Inc. v. Walsh Construction Company, LLC* [16]. North American Mechanical, Inc. (NAMI) was hired as the mechanical subcontractor by Walsh Construction, the general contractor. The project required certain subcontractors to participate in BIM, including NAMI. The project BIM was initially created using 2D drawings provided by the architect and supplemented with information from the contractor and subcontractors. NAMI developed their installation sequences using the project's BIM; however, when they started field installation, they encountered unforeseen field conditions. A subcontractor who had not been required to participate in BIM had installed their equipment in an area that NAMI was planning to install their respective equipment. This led to an overall project delay. This case highlights the importance of consistent stakeholder participation to fully realize BIM benefits, such as coordination and 4D scheduling.

2.3 Research Gaps and Study Objective

While previous research has found that BIM can provide benefits to overall project performance, there is little research focusing on how BIM-related contract language impacts the implementation of BIM and BEPs on projects. Specifically, there is a gap on how contract requirements impact specific stakeholder BIM use and the use of a BEP, as seen in Fig. 1. As illustrated in the *North American Mechanical, Inc. v. Walsh Construction* case, it is important to understand how to improve stakeholder BIM participation to enable BIM's full benefit on construction projects. Without participation of all stakeholders in the BIM process, there is the potential for disputes and claims. As an initial step to understanding how to improve project performance using BIM, researchers focused on the relationship between contracts requirements

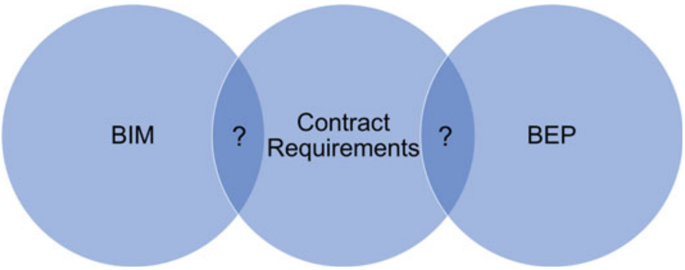

Fig. 1 Research gaps

and BIM and BEP use on the project level. The objective of this research was to evaluate the association of BIM- and BEP-related contractual requirements and BIM and BEP use on construction projects.

3 Research Approach

The research approach in this study included collecting construction project data and performing Fisher's Exact Test to identify significant associations between BIM-related contract requirements and BIM use on construction projects. This approach is illustrated in Fig. 2.

Researchers utilized a survey to capture project data from construction projects completed between 2015 and 2020. The survey captured project data using 44 multiple choice and open-ended questions, including BIM contract requirements for specific project stakeholders, the contractual requirement of a BEP, and the implementation of a BEP. Researchers utilized Qualtrics to host the online survey and it was distributed via email and LinkedIn. Data was collected between March 2020 and May 2020. Researchers then used Fisher's Exact Test to identify significant association between categorial attributes. Fisher's Exact Test relies on 2 × 2 table to measure the association between attributes as illustrated in Fig. 3. The 2 × 2 table is populated with frequencies that represent the projects within the sample that have the listed attributes.

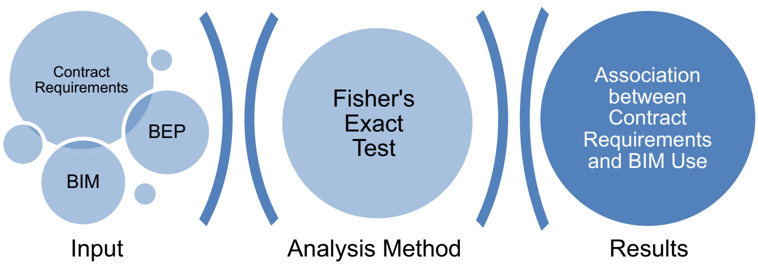

Fig. 2 Research approach

Fig. 3 Example of a 2 × 2 table for fisher's exact test

		BIM is Contractually Required	
		Yes	No
BIM is Used	Yes	a	b
	No	c	d

The null hypothesis of Fisher's Exact Test is that there is no association between attributes. Researchers selected this test and determined it was appropriate for this study as it can be used on small sample sizes [13], similar to those collected in this study. In this study, researchers wanted to test the association between the BIM contractual requirement of a stakeholder and their respective BIM use on a project, and the association between contractually requiring the use of a BEP and the implementation of a BEP on the project.

4 Results

4.1 Survey Results

The survey was opened 97 times and 71 responses were recorded with at least one survey question answered. The recorded responses were not all complete surveys and did not necessarily include all project information relevant to this study. Researchers identified 28 projects that met the criteria for this study. To be included in this study, the survey response had to include data related to BIM use of key stakeholders (architect/engineer, contractor, and subcontractor), their respective BIM contract requirements, BEP use, and BEP contract requirements. Of the 28 projects submitted, 23 projects were located in the US and five were outside of the US. Three primary project types were submitted, buildings, infrastructure, and light industrial. Table 1 breaks down the project type.

Table 2 shows the breakdown of projects by delivery method. The primary delivery method of the projects analyzed in this study are construction manager at risk. Overall, the dataset contains more projects delivered with a less collaborative delivery

Table 1 Project type

Project type	Count
Buildings	22
Infrastructure	5
Light industrial	1

Table 2 Delivery method

Delivery method	Count
Construction manager at risk	14
Design/Build	5
Design/Bid/Build	4
Not reported	4
Design assist	1

Table 3 Results from fisher's exact test

Factor 1	Factor 2	*p*-value
Architect/Engineer BIM use	Architect/Engineer's contractual BIM requirement	0.0581
Contractor BIM use	Contractor's contractual BIM requirement	**0.0148**
Subcontractor BIM use	Subcontractor's contractual BIM requirement	**0.0002**
BEP use	BEP contractual requirement	0.0978

Bold indicates significance at $p < 0.05$

method (e.g. construction manager at risk or design/bid/build) rather than a more collaborative method, such as design/build or integrated project delivery.

4.2 Results of Fisher's Exact Test

Researchers implemented Fisher's Exact Test to evaluate the association between BIM use and contractual BIM requirement. Table 3 summarizes the results of Fisher's Exact Test. These results indicate a significant association between contractor BIM use and contractual BIM requirement for contractor, and the use of BIM by subcontractors and their respective contractual BIM requirement.

5 Discussion

These findings identify a significant association of BIM contract requirements and BIM use on projects with respect to the contractor and subcontractor. This finding could be due to the increased awareness of owners with respect to BIM benefits during the construction phase and the resulting motivation to implement BIM during the construction phase of projects. The requirement of a contractor to use BIM could also influence the BIM requirements of the contractor's subcontractors, either through contractual requirement from the owner for the contractor's agreements with their subcontractors to require BIM or the contractor's understanding that BIM is most useful when all subcontractors are involved in developing and using the BIM. Some examples of BIM benefits during construction include 4D scheduling and coordination among trades. Considering the case of *North American Mechanical, Inc. v. Walsh Construction* [16] previously presented, if all subcontractors had been required to use BIM, increased participation in trade coordination could have resulted in less conflict in the field during equipment installation. Furthermore, it is important to leverage BIM during construction as it can positively impact project performance in terms of cost and schedule. Comparing the design and construction phases of a project, the construction cost is typically the largest cost prior to operations. The use of BIM with contractors and subcontracts could positively impact the construction phase's cost and schedule, which in turn could positively impact a project's overall performance.

Another factor that could impact the association between contractual BIM requirements and BIM use could be the result of contract templates in the US adding BIM-related language and documents. These contract documents include ConsensusDocs 301 BIM addendum [10] and the American Institute of Architect's suite of BIM documents, including C106 Digital Data Licensing Agreement, E203 BIM and Digital Data Exhibit, G202 Project Digital Data Protocol, and G203 Project BIM Protocol [1–4]. These contract templates could provide owners guidance on how to incorporate BIM language into contract documents and this guidance could lower the barrier to entry with respect to adding BIM to contract requirements. As BIM project data, including performance and contract requirements, becomes available, it will be interesting to understand the impact of these BIM documents on specific BIM uses and overall project performance.

With respect to architect/engineer (A/E) BIM use, the lack of significant association with the contract requirement could be due to the evolving standard of practice. As the industry transforms from 2D project delivery to digital project delivery, A/Es could have already adopted BIM as standard practice within their workflows. That being said, there are instances where A/Es use BIM solely to create 2D deliverables, which include 2D PDFs or 2D CAD drawings and traditional paper drawings, and the BIM is not required for handover to construction. While it is not apparent whether the lack of significant association between BIM use and contractual requirements for the A/E is due to BIM being a part of standard A/E practice or if owners simply do not require BIM due to requiring only 2D deliverables from the A/E, this represents a missed opportunity to improve information management throughout the project. This can be illustrated in the *North American Mechanical, Inc. v. Walsh Construction* [16] case, where the BIM utilized by the contractor and subcontractors was developed from 2D drawings provided by A/E. With the information being transferred from one phase to another using traditional 2D deliverables, there was opportunity for information to be lost. One way for information to be lost was during the manual recreation of information from the 2D format to BIM, which represents the information in 3D and has the capability of storing other information about objects, such as start-up information for equipment or rules that describe the object's relationship to other objects in the model [18].

The lack of significant association between BEP use and its contractual requirement highlights a possible opportunity for improvement. As BEPs can be a contract document, it is important that it is aligned with the overall contract. Often, A/Es and/or contractors are asked to develop the project's BEP after the base terms and conditions are agreed upon with the owner with the expectation that these parties will signoff on the BEP document and it will be incorporated into the contract. While the intent is to improve BIM implementation throughout the project, this is not always the case. Researchers interviewed a construction manager's (CM's) BIM manager of a large university campus project and learned about the interface challenges between design and construction when there is no contractual relationship between the parties. The CM and the designer on the project were negotiating the deliverables outlined in the BEP. At issue was the handover of the designer's BIM to the CM for construction phase use for tasks such as quantity take-offs to support estimating. The designer argued that since their contract with the owner only required 2D PDFs that the CM could use the BIM for reference only and it could not be relied upon with the same confidence as the 2D deliverables. This example highlights the potential pitfalls of inconsistent contract documents. One potential remedy for this challenge is to utilize order of precedence to prioritize the BIM as the source of information that governs when there are inconsistencies in project documents, such as 2D PDFs. One study found that 2D drawings still govern contracts even when BIM is developed for the project [17]. This practice will need to evolve to further promote and support BIM use among project stakeholders and throughout a project's lifecycle.

6 Conclusion and Future Work

This study highlights the importance of BIM contract requirements. It suggests that BIM use can be tied to BIM contract requirements and identifies potential areas of improvement for BIM implementation in the AEC industry. This study found a significant association between contractor and subcontract BIM use and their respective BIM contractual requirements. One strategy to improve BIM use at the project level is for owners and contractors can contractually require BIM use of their subtier partners. Another strategy to improve overall BIM use on a project is to explore is the role of the BEP within a project. This study found no significant association between BEP use and its contractual requirement. This finding could point to the slow transition of contract documents to formally address the process and development of BIM throughout a project as represented by a BEP. Future work can investigate BIM and its related contract requirements and its impact on project delivery and performance. Researchers could investigate the impact of specific clauses on BIM use during certain project phases and evaluate its impact on overall project performance. Furthermore, researchers could also investigate how to improve consistency between contracts and BEPs. Overall, increasing the understanding the role of contracts in BIM implementation can identify best practices and current challenges of the use of BIM to improve project delivery and performance.

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A Gap Analysis of Current CCDC Standard Contract Documents and Provisions for Successful BIM-Enabled Projects in Canada

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1 Introduction

Contracts are known as legal agreements to determine the rights and responsibilities of the parties involved. Primarily, attempts to address numerous uncertainties during construction are accomplished by devising specific provisions. However, the number of provisions could not offer better performance of a contract and instead, the content of clauses is of immense importance [27]. Thus, contractual clauses should be defined according to their specific functions. In this regard, studies have evolved from a narrow controlling function approach to recognizing a multifunctional attitude, including coordination and contingency [22]. Moreover, to avoid disputes, stakeholders identify potential infringements and attempt to incorporate them in contractual terms. The expected performance of the project results from proper contractual terms.

On the other hand, the architecture, engineering, construction, and owner (AECO) industry has been widely recognized BIM implementation as a useful technology in construction. Although BIM offers many benefits, it also causes uncertainties, specifically in the legal aspect [15]. Moreover, standard contracts merely serve as guidelines and do not fulfill their purpose in dealing with BIM projects' legal issues [1]. Despite the development of various BIM protocols and contracts, including BIM and Digital Data Exhibit [2], Building Information Modeling Addendum [13], CIC BIM Protocol [12] and BIM Contract Appendix [18], their efficient application remains low [11]. Projects are mostly executed using conventional contracts, which are not in tune with the collaborative nature of BIM [3]. This issue emphasizes the importance of developing BIM contracts; otherwise, BIM projects cannot fully

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deliver their purposes. However, research on BIM contracts and pertinent legal issues are still immature [16].

Therefore, the study presented in this paper aims to review legal issues related to BIM implementation and to realize how contractual language can be adopted in amending provisions related to legal aspects in the Canadian context. The literature review was performed in two sections to cumulate current knowledge pertinent to both parts of the research objective, including issues in conventional contracts and BIM agreements alike.

To analyze the data collected from the literature review, a content analysis system was applied using NVivo. This research investigated the dual impact of contractual language and legal issues in BIM-enabled projects as a gap in the current literature review. The results indicate that intellectual property rights (including copyright) and digital model ownership are not included in CCDCs. Moreover, collaborative roles, namely BIM manager, are not defined. Standard of care has been ignored. The liability issue is not clear, and finally, the security of data has not been discussed. An overview of legal issues in CCDCs and current BIM contracts has been developed in the result section. The discussion part will provide probable suggestions for dealing with those legal aspects.

2 Research Background

2.1 Contractual Language

Contractual provisions can include multiple functions [22]. Mellewigt et al. [27] investigated various studies on contractual aspects and realized that researchers had adopted different approaches. The existence of diverse trends indicates the need for a unanimous conclusion about the contractual dimension to be applied in analyzing contracts [27].

Many researchers have mentioned safeguarding, coordination, and contingency adaptability as provisions' functions (e.g., [22, 27]. The controlling provisions' primary feature is to deal with cooperation situations between the involved organizations [24] and clarify the party's rights and obligations [29]. These can be achieved within specific sanction clauses and obligatory penalties [33]. Meanwhile, safeguarding stakeholders' benefits is merely one aspect of contracts [33]. The coordination function is another element that defines each party's roles in increasing the collaboration level and decreasing the misinterpretation risk [29]. Coordination clauses attempt to provide the proper connection between parties [25]. Safeguarding and coordination functions' goal is to justify incentives and illuminate partners' responsibilities before signing the agreement [27]. However, contingency adaptability is another framework providing guidelines in adaptation to uncertainties that are likely to happen during the collaboration process [22].

On the other hand, damaging outcomes, including lack of trust, mostly stem from focusing on a specific function of the contract, while a sufficient level of each function can alleviate those undesirable results. It can be achieved through allocating a fair number of risks between stakeholders [22]. Lumineau [24] stated that too much reliance on the controlling function might enhance the adverse outcomes of distrust. It can also provoke the parties' win-lose attitude, which will cause self-protection approaches toward the other party [24]. Moreover, it decreases trust and cooperation among stakeholders [22].

As well, You et al. [32] argued that minimizing opportunistic behaviour is not always reached within controlling provisions, but coordination function can enormously influence the association between behavioural uncertainties and opportunistic behaviour. Furthermore, Mellewigt et al. [27] mentioned that the complexity and completeness of contracts are bound with the level of detail covered in the agreement. In terms of complexity, You et al. [32] highlighted the cost of designing a complex contract and concluded that complexity could not include all respects of an agreement. Their study outcomes indicate that controlling and contingency functions in contracts can impact opportunistic behaviour resulted from environmental uncertainties, while coordination affects opportunism influenced by behavioural unpredictability. Regarding contractual completeness, if a contract tends to include every issue, it will be so complicated that even the main subjects might be misunderstood or neglected. This situation will eventually result in opportunism [23].

Moreover, Lu et al. [23] claimed that adding several specific requirements to a standard contract which already includes general and special conditions, will bring about distrust. Therefore, contractors will focus more on their profits leading to the breach of contract and opportunistic behaviour. Additionally, a too much-completed contract clarifying responsibilities and risks in detail may lessen the party's willingness to share information and lower trust [19].

Cheung and Pang [10] stated that since contracts are inevitably incomplete, they do not protect the project from facing risks and uncertainties. It may lead to construction disputes. Ambiguity, inconsistency, and defectiveness are the elements of incompleteness (Cheung et al. 2013). In this regard, Malhotra et al. (2011) declared that contracts are incomplete for varied reasons; thus, disputes are unavoidable [33]. Therefore, in devising contracts, stakeholders should avoid ambiguous and unclear contractual language while considering that too much coverage of detail is not desirable.

2.2 BIM Contractual Languages

It is mentioned by Taylor [31] that successful implementation of BIM requires changes in contracts. Regarding contractual dimensions in BIM projects, a variety of legal issues have been identified by researchers [28]. Alwash et al. [3] identified professional liability and duty of care, authorship, intellectual property, and acceptability of digital documents as the major concerns in contracts. Fan [15] argued that the construction industry has not succeeded in addressing legal issues, risks and barriers of BIM and further highlighted intellectual property rights (IPR) as the primary issue in BIM agreements. Besides, legal responsibilities are not clearly defined for BIM projects. Thus, the party's roles and responsibilities require to be specified in the BIM execution plan.

Meanwhile, clarifying contractual relationships among key members facilitates justifying their connections in the BIM execution plan [11]. Chong et al. [11] also added that standard of care and the BIM model's security are other significant legal aspects. Kuiper and Holzer [20] highlighted the common themes of the BIM legal aspects, including intellectual property, model ownership, liability, right to rely on, shifting of risk, the standard of care and BIM compensation. Eadie et al. [14] mentioned model ownership, shifting of risk, data reliance, model responsibility, intellectual property and sharing of copyright data, standard of care, BIM compensation, design, and software liability. Moreover, aspects comprising compensation and consideration, conditions of the contract, data security, intellectual property and interoperability have been introduced as legal considerations by Abd Jamil et al. (2020).

3 Research Methodology

To provide an overview of contractual issues, an in-depth literature review was performed in multiple rounds and served to identify several factors that have been highlighted as problematic within contracts. After the first round of review, a coding system using NVivo 12 was created based on the legal factors identified and was used in subsequent rounds to analyze related studies. Aiming at analyzing the qualitative material exerted from the literature review, a content analysis approach was adopted. Content analysis is a detailed exploration of a specific material's context to identify patterns, trends or themes. The identified legal issues, including intellectual property, ownership, roles and responsibilities, liability, standard of care and security of data, were turned to codes, and then the articles' context was marked with a code best describing it. Afterward, the word frequency was determined. The results are expressed in Table 1.

Table 1 word frequency of BIM legal issues

Code	References
Intellectual property	11
Ownership	10
Roles and responsibilities	8
Liability	7
Standard of care	6
Security	5

Furthermore, CCDCs and BIM contracts were carefully analyzed to understand how they cover the legal issues identified. Although this study may not be comprehensive research of all BIM legal aspects, the aim was to investigate further this area's gap. Hence, the identified codes' credibility will be examined through a survey and interviews in the next step of this research project.

4 Results

The outcomes of analyzing the articles associated with BIM legal issues are shown in Table 1. It indicates the frequency of potential legal aspects (as codes) in the context of 22 research. Intellectual property, ownership, roles and responsibilities, liability, standard of care and security have been found to be the most concerning aspects.

Furthermore, this research has developed the above-mentioned legal issues framework to analyze the CCDC contracts (2, 5, 14, 30). The gaps in the current CCDCs through the lens of those potential legal issues are highlighted in Table 2. Additionally, current BIM contracts, including IBC, ConcensusDoc301, AIA and CIC, were examined regarding the same legal dimensions as illustrated in Table 3. Further description of identified codes (legal aspects) and their justification in CCDCs and BIM contracts will follow.

4.1 Intellectual Property (IP)

Intellectual property is among the significant legal challenges in BIM contracts (Kuiper et al. 2013). Common intellectual property rights comprise copyright, trademarks, patents, and industrial design rights [17]. It is alleged by Ashcraft [5] that current IP issues are like those that existed before BIM, which is magnified due to the information load in BIM models and the simplicity of transmitting them. BIM model sharing with the design team members and the client without restricting the information flow may lead to plagiarism [14]. Besides, a third party might face claims related to breaches from the model; thus, it is of utmost importance to clarify the intellectual property rights at the modelling commencement [16] (Abd Jamil et al. 2020). Furthermore, as project information can be shared among the stakeholders, the models' copyright ownership may become a source of disputes [17]. However, according to the case studies by Abd Jamil et al. (2020), the client asserted a lack of specific contractual clauses regarding how IP can be protected considering the creation of models in a collaborative setting.

While all BIM contracts (IBC, Consensus Doc 301, AIA, CIC) recognize each contributor of the model as the IP ownership of their contribution, CCDCs do not clarify this issue. Reviewing CCDC contracts indicted that the IP issues are not considered in CCDC 2 and 5 whatsoever. Although CCDC 14 marks the copyright issue, it does not include digital models. CCDC 30 refers the stakeholders to the IBC

Table 2 BIM legal issues in CCDCs

	Intellectual property	Ownership	Roles and responsibilities	Liability	Standard of care	Security
CCDC 2 [6]	Not addressed	1-Absense of digital models 2-Absense of the owner's right to keep the models for project's lifecycle	BIM roles are not defined	Liability of design is not clarified	Not addressed	Absence of data security
CCDC 5 [7]	Not addressed	1-Absense of digital models 2-Absense of the owner's right to keep the models for project's lifecycle	BIM roles are not defined	Liability of design is not clarified	Not addressed	Absence of data security
CCDC 14 [8]	Copyright of digital models are not included	1-Absense of digital models 2-Owner can just keep models he paid for	BIM roles are not defined	limited to liability of design services	Not addressed	Absence of data security
CCDC 30 [9]	If using BIM, copyright is based on IBC	1-Absense of digital models 2-Owner can just keep models he paid for	BIM roles are not defined	Not clarified	Not addressed	Absence of data security

contract whenever BIM is being applied in the project. Since BIM models are created collaboratively, the IP issues related to its elements and the whole model should be clarified within the provisions.

Table 3 Legal issues in BIM Protocols

	Intellectual property	Ownership	Roles and Responsibilities	Liability	Standard of care	Security
IBC	Copyright is for model element author	Each model author grants the owner license for project lifecycle	Role of model manager is not defined in detail and it will be determined based on party's agreement	Liability of parties is limited to direct damages	Defined based on agreement or law	Absence of data security
Consensus Docs	Each model contributor has the IP of their contribution	Each model contributor has the ownership of their contribution (owner has the copyright license of the model for project lifecycle)	BIM manager's role and responsibilities are defined	Each model contributor has the liability of their contribution	Defined based on agreement or law	Absence of data security
AIA	Transmitting party has the copyright ownership or the right to transmit it	Transmitting party has the ownership or the right to transmit it	Model manager's role and responsibilities are defined	Not addressed	Not addressed	Defined by model manager and users of the model
CIC	All rights (including copyright) belong to team members	The owner has the model ownership	Information manager responsibilities are defined	Excluded to those who have license	Defined based on agreement or law	Not addressed

4.2 Ownership

One of the most fundamental decisions in BIM-enabled projects is who owns the BIM information after project completion [5]. Oraee et al. [28] pointed out the importance of deciding who would allocate resources to preserve the model throughout the entire building life cycle. According to Arensman and Ozbek [4], the owner claims the building model for facility management. Although the ownership of digital models is not clearly mentioned in IBC and Consensus Docs, Larson et al. [21] believe that "Absent contract language to the contrary, the party that creates the model owns it." Furthermore, model authors are compelled to grant a non-exclusive license to each participant to use the model for that specific project only.

Moreover, the owner receives a license for using the model during the project lifecycle according to the IBC contract [18] and Consensus Docs [13]. Alwash et al. [3] referred to the standard form of agreement between owner and architect and highlighted that the models' ownership belongs to the authors. Regarding AIA's E203 [2], the transmitting party has the ownership of the model or the right to transmit it. While receiving party is not considered the model's owner, they do not have the right to modify or transmit such data to other participants. This limitation could also include the operation phase [3]. On the other hand, CIC [12] recognizes the owner as the digital models' possessor, which illustrates that the current ownership approach is still subjective.

On the other hand, CCDC contracts (2, 5, 14, 30) do not address digital models' ownership. Besides, the owner's right to retain the models after ending the project should be considered.

4.3 Roles and Responsibilities

While in the current legal system, responsibilities are well defined, they may not be innate in a BIM project (Arensman et al. 2012). Thus, there is a need for transitions in roles and legal responsibilities for projects in which BIM is utilized. Besides in creating BM models, several parties are involved; therefore, the BIM Execution Plan should provide checklists and standards for project implementation [16]. However, BIM Execution Plan is not always among contract documents; thus, uncertain roles and responsibilities bring about legal liabilities [26]. Meanwhile, Kuiper et al. (2013) pointed out legal issues in conventional contracts regarding BIM project participants' roles. Alwash et al. [3] also supported this notion and stated that conventional contracts offer a single point of responsibilities, while in BIM contracts, liabilities are jointly shared among various disciplines.

In this regard, the crucial collaborative role in BIM projects was reviewed in contracts. This role, along with its responsibilities, is defined as BIM manager in consensus 301, the model manager in AIA and information manager in CIC. IBC contract mentions the model manager role; however, its responsibilities are not predefined and should be written upon the parties' agreement. Moreover, CCDCs lack covering such a collaborative role and its responsibilities in case of utilizing BIM.

4.4 Liability

Ashcraft [5] stated that there is a vital deterrent toward adopting BM as it enhances the designer's potential liability. Moreover, when an error occurs, specifying liability and reparations may not be straightforward due to the model's multi parties' contribution. While success and liabilities in the created model are shared between designers [3], parties often attempt to avoid liability in their outcome (Larson et al. 2007). Until there is no systematic support available to control this process automatically, stakeholders continue shifting blames to the other party [3]. On the other hand, Kuiper et al. (2013) claimed that if all parties agreed upon a decision, determining the source of data or error may not be easy, specifically when stakeholders are not contractually connected. In such cases, the decision around collective liability will depend on the project players. Also, if a contract does not mention liability or the risk nature is beyond the contract scope, the decision on the loss incurred should be made according to the customs or jurisprudence [17].

According to the IBC contract, the liability of parties is limited to direct damages. Consensus Docs recognizes each model contributor liable for their contribution. CIC pointed out that liability only includes those among project team members and employer who are granted licenses. However, the liability issue is not mentioned in the AIA document. Furthermore, the liability of design in CCDC 2, 5 and 30 is required to be clarified. CCDC 14 only covers the design liability and lacks other aspects. Thus, all the CCDC contracts need to specify liabilities regarding the collaborative nature of BIM projects.

4.5 Standard of Care

After defining liabilities or obligations, the next step is to clarify the standard of care [11, 17]. Fan et al. [16] stated that doctrines, including the "Privity of Contract" and the "Spearin doctrine", can be stipulated in the contracts. Considering that creating digital models is of significant importance in BIM projects, the client requires designers to fulfill their tasks in line with professionals in that field. Conforming to the standard of care helps prepare a detailed model and prevents conflicts [5]. Arensman et al. (2012) stated that as BIM can detect conflicts to avoid mistakes, the standard of care is expected to advance. Ashcraft [5] claimed that addressing conflicts in the field or through post-design coordination drawings is not admissible.

Defining the standard of care in IBC, Consensus Docs and CIC document is based on the party's agreement, while AIA does not address this issue. Moreover, CCDCs (2, 5, 14, 30) lack addressing this concern.

4.6 Security

Abd Jamil et al. (2020) define security as issues pertinent to protect confidential information by project members, which most concern general contractors. By safeguarding data, planning for risks stemming from loss or corruption of data is not required (Abd Jamil et al. 2020). Digitalization of BIM information paves the way to extract and reuse the data at ease [15]. Thus, it gives rise to how the information can be protected [11]. Fan [15] mentioned that a "Quick Response Code (QR-Code)" had already been applied to optimize information flow in BIM projects. This technology can prevent breaches or copyright issues related to BIM drawings and documents. Further, to prevent transmitting any inaccurate information from the BIM model, a data exchange plan is needed [16].

Security of data is not pointed out in IBC, Consensus Docs and CIC; however, AIA highlighted that Model security requirements should be defined by the model manager and other model users. Furthermore, none of the CCDC 2, 5, 14 and 30 considers data security as a contract provision.

5 Discussion

The primary aim of this research was to answer the question as to how contractual language and legal issues can impact BIM projects. In this regard, reviewing the literature indicated that contractual provisions have three functions: safeguarding, coordinating, and contingency adaptability. Meanwhile, Kuiper et al. (2013) suggested that depending on the extent to which BIM is used in a project, legal risks pertinent to digital models should be involved in the contract to deal with limited contractual documentation. Thus, identified legal issues in this paper can be allocated to those triple functions. Intellectual property, ownership, security, standard of care and liability issues are determined through safeguarding clauses, while roles and responsibilities are considered the coordination dimension.

In devising controlling clauses, stakeholders are advised to involve lawyers and experts to detect inadequacies and correct them [30]. Although clarity in defining safeguarding provisions is of high importance, parties must avoid too much emphasis on them. Therefore, applying proper contractual terms is crucial. Key terms also should be defined to avoid misinterpretations and opportunistic behaviour. Furthermore, contractual relationships specifically for the key parties, including the BIM manager, should be clarified through coordinating provisions. It may help the stakeholders in formulating required responsibilities in the BIM execution plan.

Moreover, as the results illustrated, current CCDC documents do not fully cover legal issues pertinent to BIM models. IPR (Intellectual Property Rights), which includes copyright issue, along with model ownership, liability, the standard of care, security of data and BIM roles and responsibilities, require strong attention. Besides, to support legal dimensions in Canadian BIM projects, some modifications in the IBC contract are essential. The responsibilities of the BIM manager should be predetermined in the context of the agreement. Furthermore, the liability and security of the model are missing in the current version.

This research highlighted the gaps in CCDCs and BIM contracts. It also emphasized the role of collaborative contractual language, which could clarify BIM-related legal issues.

6 Conclusion

This research aimed to identify controversial aspects in contracting and review the most problematic BIM legal issues. To achieve this goal, sensitive areas of general contracts were identified through triple contractual functions, namely controlling, coordinating and contingency. Then potential legal aspects of BIM contracts were recognized through a coding system in NVivo. Finally, to devise a more practical BIM contract, some recommendations were represented.

While numerous studies have investigated legal issues in BIM contracts, this research adopted another approach and attempted to investigate BIM legal issues from a contractual language perspective in CCDCs. A survey methodology will be applied in future to connect these theoretical findings to the industry perspective.

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A Framework to Determine the Optimal Locations of Temporary Debris Management Sites in Response to a Hurricane Event

Navid Nickdoost and Juyeong Choi

1 Introduction

Each hurricane disaster emphasizes the importance of debris management. The huge amount of disaster debris may prevent emergency vehicles from accessing vital infrastructure. Moreover, various debris types, including hazardous waste and organic waste, may threaten the community's health and safety [1]. Therefore, it is crucial to develop detailed plans for managing disaster debris removal operations to enhance the community's health and safety. Developing such plans requires sufficient understanding of how different debris removal system components work to relocate the debris and recover the affected community [2, 3]. One such component is temporary debris management sites (TDMS), which serve multiple roles, including sorting, storing, and recycling disaster debris [4]. The number and location of TDMSs impact the pace of recovering the affected community since they control the operation of other system components such as debris-removing vehicles [5]. Thus, a framework is required to select the optimal TDMS locations and to establish effective debris removal plans that improve post-disaster debris removal operations [1].

The location of a TDMS depends on various factors ranging from legal (e.g., ownership of the land), geographical (e.g., relative distance to rivers), to social (e.g., community health and safety) [6]. These sites should be close enough to the impacted area to expedite the debris collection process and preferably on public land. However, they should maintain enough distance to various geographical regions, including floodplains, wetlands, residential locations, and environmentally sensitive areas [1]. Identifying appropriate TDMS locations is considered a suitability analysis [2]. Grzeda et al. [7] used cluster analysis and GIS to identify TDMS locations. Habib

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and Sarkar [4] employed multi-criteria decision-making techniques, including ANP and fuzzy TOPSIS, to select the best locations among several alternatives. Cheng and Thompson [6] provided a list of TDMS location characteristics based on the existing literature and employed the AHP method, Boolean logic, and GIS analysis to find the possible locations for TDMSs. These studies rely on geographical factors to identify TDMS locations. However, the location of the TDMS also affects the time and cost of debris removal operations. Therefore, in order to maximize the performance of debris removal plans, any approach for selecting TDMS locations should consider post-disaster debris removal operations as well as geographic requirements.

Multiple studies investigated post-disaster debris removal operations to improve the performance of the post-disaster recovery strategies. Particularly, a number of studies assessed the scheduling of debris-removing resources (e.g., trucks and dozers) to find the optimal set of routes for the fleet of debris-removing vehicles. Optimizing debris-removing vehicle routes is generally considered a vehicle routing problem [2]. The objective is usually to minimize the cost of providing service (i.e., removing debris) or the total travel distance (time). Various approaches have been proposed to solve this problem, including global optimization techniques and metaheuristics [8]. For example, Brooks and Mendoca [9] proposed using queuing theory to optimize debris hauling vehicles' allocation. Lorca et al. [10] developed a spreadsheet-based decision support tool to assist disaster management authorities with collecting, transporting, recycling, and disposing of disaster debris. Although these studies propose efficient strategies to optimize a specific component of the debris management system or the entire system, these approaches do not provide a platform to simulate and visualize the behavior of each component of the system throughout the optimization process. Visualizing post-disaster debris-removal process enables decision-makers to monitor the operations of the system in planning scenarios, to readily detect the systems' bottlenecks, and thus to develop more effective debris management plans.

To fill these gaps, a framework is proposed to determine the optimal locations for TDMSs. The proposed framework integrates geographic requirements and debris management system operations to facilitate the selection of optimal TDMS locations. The framework employs GIS analysis and a simulation-based optimization method to find the best TDMS locations while helping decision-makers monitor the behavior of different components of debris management systems. Simulation approaches enable decision-makers to easily model the complexities of the real-world conditions and provide a comprehensive understanding of each system component's behavior and the dynamics of the entire debris management system. In this paper, the agent-based modeling (ABM) approach is employed to simulate post-disaster debris collection operations. The ABM method allows decision-makers to model the complex behavior of different system components and evaluate and monitor their performance in various scenarios. Simulation approaches have been previously employed to model solid waste management systems to support decision-making [11, 12]. The proposed framework will be presented in the next section, followed by a demonstration of its application through a case study of the debris removal operation for Liberty County, Florida, in a hypothetical hurricane scenario.

2 Methodology

The framework consists of three main modules: (1) suitability analysis, (2) operation simulation, and (3) optimization module (Fig. 1). The suitability analysis module aims to identify the potential areas that meet the geographic criteria for TDMSs. The next module simulates the disaster debris removal operation based on feasible TDMS locations (i.e., the outcome of the suitability analysis), estimated generated debris, and debris removal resources (e.g., trucks). Finally, the optimization module finds the optimum TDMS locations for the given debris estimates and available resources and provides detailed debris removal plans. The detailed information for each section is described in the following sections.

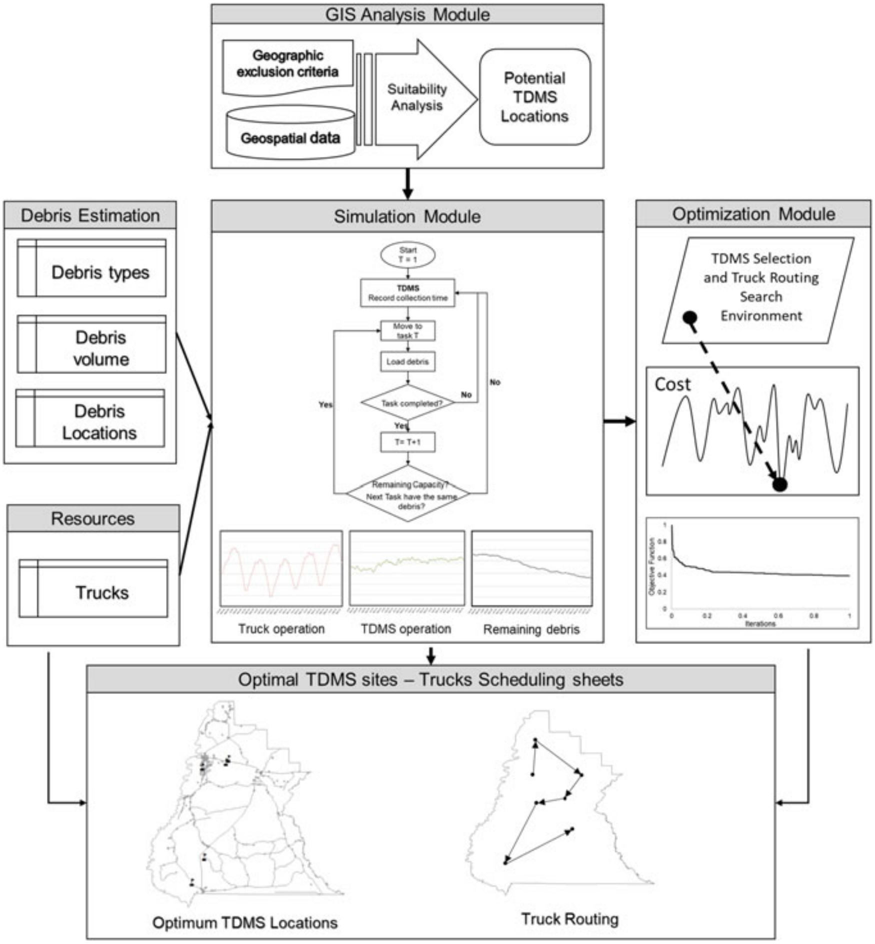

Fig. 1 The proposed framework for identification of the optimal locations for TDMSs

2.1 Suitability Analysis Module

The suitability analysis module starts with identifying the inclusion and exclusion criteria for the TDMSs locations. These criteria specify the required geographical characteristics of the TDMSs. According to the EPA [1], TDMSs should be located at an appropriate distance from wells, rivers, lakes, floodplains, wetlands, environmentally sensitive areas, residents, and cultural properties. Moreover, they should have sufficient size and accessibility [1]. A literature review is conducted to determine the constraints for TDMS location. Table 1 presents the required exclusion criteria, along with the corresponding constraints. Once the criteria are identified, the geospatial data for each criterion should be collected and maintained in the data repository of the framework.

Following the approaches proposed by Kim et al. [2] and Cheng and Thompson [6], a restriction model is developed to specify the feasible places for the TDMS [2, 6]. The restriction model, which is depicted in Fig. 2, generates buffer zones to specify the restricted area. Then, feasible locations are identified by removing the restricted area from the area of interest. ArcGIS Model Builder tool was utilized to develop this model.

Next, the feasible locations are ranked based on their suitability. Previous studies have employed different approaches to select the most suitable TDMS sites. These include ranking the sites considering the total truck travel time [5] and the weighted overlay of suitability criteria [4, 14]. In this analysis, five criteria are selected to rank possible locations for suitability: the distance to urban buildings (residential,

Table 1 Summary of criteria and constraints considered

Criteria	Description	Constraint
Wetlands (Cheng and Thompson [6])	Lakes, reservoirs, streams, bays, springs, open water, wetland forests, vegetated and non-vegetated wetlands	Not in the 180 m buffer zone [13]
Agricultural lands and forests (Cheng and Thompson [6])	Cropland, tree crops, specialty farms, nurseries and vineyards, feeding operations, mixed forests, coniferous forests, tree plantations, hardwood forests	Not located in agriculture and forests (Cheng and Thompson [6])
Urban land use (Cheng and Thompson [6])	Residential, institutional, recreational, commercial, extractive	Not located in selected urban land use (Cheng and Thompson [6])
Transportation and utilities (Cheng and Thompson [6])	Transportation utilities and communication	Not in the 200 m buffer zone (Cheng and Thompson [6])
Industrial sites [2]	Industrial sites	Not located 500 m buffer zone [2]
Flood zones [2]	100-year flood plain	Not located in flood zones [13]

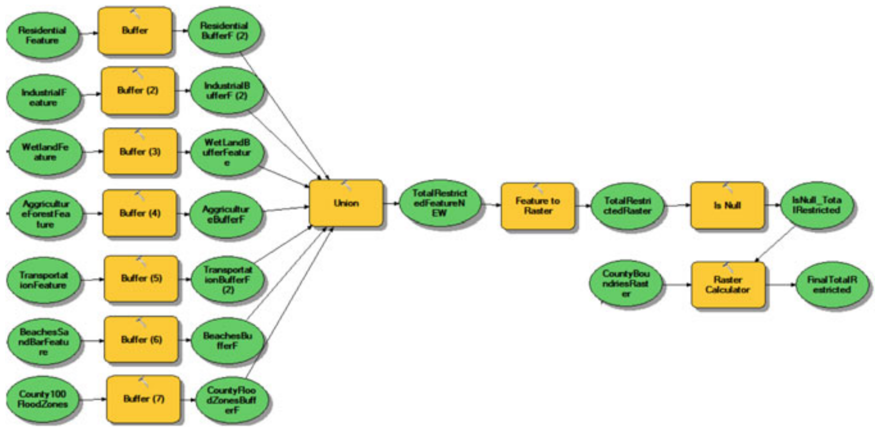

Fig. 2 Restriction model

commercial, institutional), wetlands, green lands (agricultural and forests), and transportation roads, and slope [4]. The Euclidean distance of county pixels to each type of land use is calculated. Then, the resulting rasters are classified into five different classes based on their corresponding criteria [14]. Finally, the weighted overlay tool is used to combine these classes. The relative weights for each criterion are adopted from [4]. Lastly, feasible sites bigger than 2 hectares are reported and ranked based on their suitability [6].

2.2 Operation Simulation Module

As explained previously, it is essential to consider the disaster debris removal operations for the selection of TDMS sites. In other words, the location selection problem and debris removal operation problem should be considered in an integrated manner since the state of one problem impacts the other. In this paper, the agent-based modeling (ABM) approach is employed to simulate the post-disaster debris hauling operation. An ABM approach models the system as a collection of autonomous entities, called agents. The agents make decisions according to their assessment of the environment and following their predetermined set of rules [15]. The ABM approach has been widely used to support different aspects of decision-making in disaster risk reduction, including decreasing community vulnerability [16] and post-earthquake search and rescue operations [17].

AnyLogic 8.7.2, an object-oriented programming simulation tool, is used to simulate the debris collection process. The simulation module first models the roadways using GIS space markup properties of the AnyLogic software. In this regard, shapefiles of the road network of the desired geographical area are imported to the

AnyLogic GIS environment. Once the road network is generated within the simulation model, model agents are populated. Specifically, the model has three different agent types: TDMS, truck, and debris. Each agent type is modeled as a population of agents and imported into the AnyLogic GIS environment based on their geographic information.

The TDMS agents are modeled as stationary warehouses. In this paper, the capacity of the TDMSs is assumed to be infinity. In other words, these sites can handle as much debris as is delivered to them. Moreover, the internal operation of the TDMSs is not modeled in this paper. It is assumed that the trucks arrive at the TDMS, wait for 10 min to dump the debris, and either return to continue their assigned tasks or move on to their next task.

The debris agents represent debris removal tasks assigned to debris-removing vehicles. Debris agents have the following information: debris type, weight, and geographical location. In pre-disaster situations, this information can be estimated using debris estimation tools such as FEMA HAZUS-MH [18]. In post-disaster conditions, the amount and type of the generated debris can be evaluated based on field surveys and analysis of aerial images [19].

The truck agent is modeled as a moving vehicle. This agent has a capacity parameter that represents the maximum debris volume that it can carry. Moreover, a unique list of debris removal tasks will be assigned to each vehicle at the start of the simulation process. The truck agent movement's logic (Fig. 3) is modeled using statecharts within the AnyLogic environment. Each truck agent starts to collect disaster debris based on the list of tasks assigned to it. Once the debris is loaded, the truck agent checks its remaining capacity. If there is no remaining capacity, the truck moves to the closest TDMS to unload the collected waste. The vehicle moves on to the next task after completing an assigned task if (1) it has some available capacity and (2) the following task has the same type of debris as is currently loaded. In any case, each truck needs to complete a task before moving on to its next task. In other words, a truck may return to the same node multiple times before moving to the next task if the debris volume is greater than the available capacity of the truck.

2.3 Optimization

The optimization module aims to find the near-optimal solutions for the TDMSs locations while considering the geographical requirements of TDMSs and the debris removal operations duration. The optimization algorithm searches for various combinations of the available TDMS locations and truck routes to find the one that results in the best performance (i.e., least collection time). Equation (1) shows the objective function of the optimization problem. Note that the optimization module uses the simulation model to evaluate this objective function.

$$\text{Min(Total Debris Collection Time)} + \text{F(distance to transportation roads)}$$

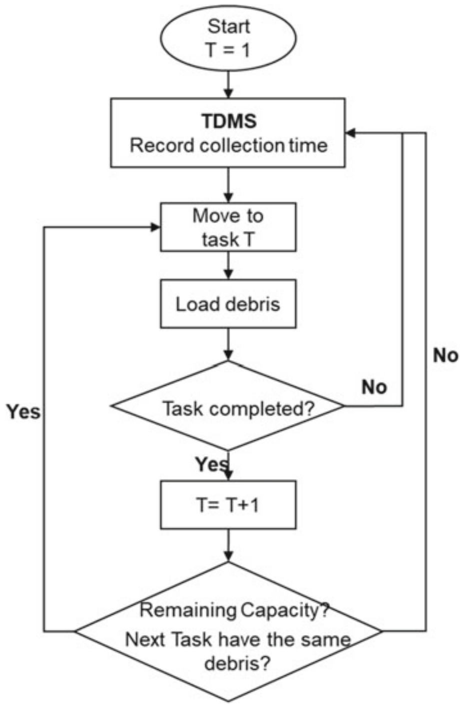

Fig. 3 Truck movement logic

$$-\text{–F(distance to urban buildings)–}-\text{F(distance to wetlands)}$$
$$-\text{–F(distance to green lands)} + \text{penalty} \quad (1)$$

In this equation, F(.) is a linear function that converts the calculated distance to time, based on the truck speed.

This model integrates debris removal operations with the geographical criteria to select the near-optimum locations for TDMSs by including four previously used criteria in the objective function. Since the objective function is minimization, the 'minus' signs represent the components that favor higher values. Meanwhile, the optimization search engine explores different scenarios of TDMS selection and assigning debris collection tasks to minimize the overall duration of the debris collection process. Each truck collects the debris based on the assigned tasks following its behavior logic (Fig. 3), and the total collection time is reported. The objective function is then calculated as the sum of all the trucks' collection time along with the geographic requirement for TDMSs.

It is necessary to expedite the collection of hazardous/organic debris to minimize adverse effects on the affected community. Moreover, the optimization algorithm should prioritize collecting the debris in urban communities to accelerate the recovery of the community. To have the search algorithm prioritize such debris for collection, the algorithm incorporates penalty functions. Specifically, the algorithm penalizes the case where hazardous or perishable debris is delivered to the TDMS after its assigned time constraint. The time constraint can be defined, for example, based on the changing property of the materials (e.g., organic waste) over time [20]. The penalty increases as the duration of delivering debris increases beyond the time limit (Eqs. 2 and 3).

$$\text{penalty} = \sum_{1}^{m} p_i \tag{2}$$

$$p = f(t_h) + g(t_c) \tag{3}$$

In Eq. (2), p is the penalty time for each debris collection task, m is the total number of tasks to perform. Also, in Eq. (3), $f(t_h)$ is a function of the extra time spent to collect and deliver hazardous/perishable debris and $g(t_c)$ is a function of the extra time spent to collect and deliver debris from urban communities, respectively.

To find the optimal TDMS location, a vehicle routing problem should be solved. In this paper, the AnyLogic optimization engine is employed to solve this problem. This engine is built upon the OptQuest Optimization Engine, which uses metaheuristics to find near-optimal solutions. The optimization model is developed and customized using the Custom Experiment capability of the AnyLogic software. The Custom Experiment calls the AnyLogic optimization engine and runs the simulation model to calculate the objective functions at each iteration while varying the TDMS locations as well as the list of tasks assigned to each truck as design variables. The AnyLogic optimization engine evaluates one possible solution per iteration and keeps the best solution found during the optimization process. As the result of the optimization process, the best locations of TDMSs and the corresponding truck routing schedule will be found.

3 Debris Removal Planning for a Hypothetical Hurricane Event

In this section, the application of the proposed framework is demonstrated using a case study of debris removal operation for Liberty County, Florida, in response to a hypothetical hurricane event. The test scenario is developed to identify near-optimum TDMS locations during the recovery phase. The required geospatial data for suitability analysis was collected from multiple sources, including the FDEP Open Data Portal (statewide land use and cover data), FDOT GIS data repository (statewide road network data), USGS (elevation), and FEMA statewide flood hazard area (flood plains). The total debris volume was estimated using HAZUS-MH based on the assumption that a major hurricane affects Liberty County; about 160,000 cubic yards of mixed debris was generated with the Hurricane Michael scenario (10 years

Table 2 Attributes of the test scenario

Attributes	Value
Total debris volume (C.Y.)	160,000
Total debris locations	300
% of hazardous debris	50%
% of total debris in urban communities	50%
Number of debris removing crews	10
Number of trucks per crew	5
Trucks capacity (CY.)	18
Number of required TDMS	5
Number of suitable sites for TDMS	45

event). The other debris information, including type and location along roadways, was generated randomly. Table 2 summarizes the attributes of the test scenario.

According to the framework, the first step of locating near-optimum locations for TDMSs is identifying suitable areas meeting the geographical criteria specified in Table 1. Following the model depicted in Fig. 2, the restricted areas were identified, and their suitability was assessed according to their slope and distance to urban buildings, wetlands, green lands, and transportation roads. Figure 4 depicts the possible areas for TDMS along with debris locations. According to the analysis, most of the feasible areas are ranked "two" (i.e., average). A few locations in southern Liberty County were rated as ideal for TDMS (i.e., ranked "Three"). Although these sites are far from populated areas (i.e., the area specified by the red box in Fig. 4), they might be ideal for collecting debris located along the county's southern roads. Therefore, a combination of suitable areas from these categories should be selected to minimize the duration of debris collection.

Following the second module of the framework, a model was developed to simulate the post-disaster operation. The simulation model consists of three types of agents: trucks, TDMS, and debris. As explained in Table 2, the test scenario assumes that fifty debris removing trucks, with a collection capacity of 18 cubic yards each, are available to collect the debris. Each five trucks are grouped into one debris removal crew as suggested by FEMA [21]. The trucks in one crew work collectively to remove the debris from roadways based on tasks assigned to them. The model simulates five TDMS agents selected out of 45 identified suitable lands. Three hundred debris agents were randomly populated along the roadways to represent the total generated debris. Overall, about 50% of the total debris volume was marked as hazardous/perishable debris with high priority for collection. Similarly, about 50% of the total debris volume was located within the community. The model prioritizes hazardous debris and the debris located in residential areas (i.e., debris located in the red box in Fig. 4) to accelerate the communities' recovery and minimize health threats.

The optimization module searches for the optimum combination of TDMS locations and truck routing schedule to minimize the overall debris collection time. The

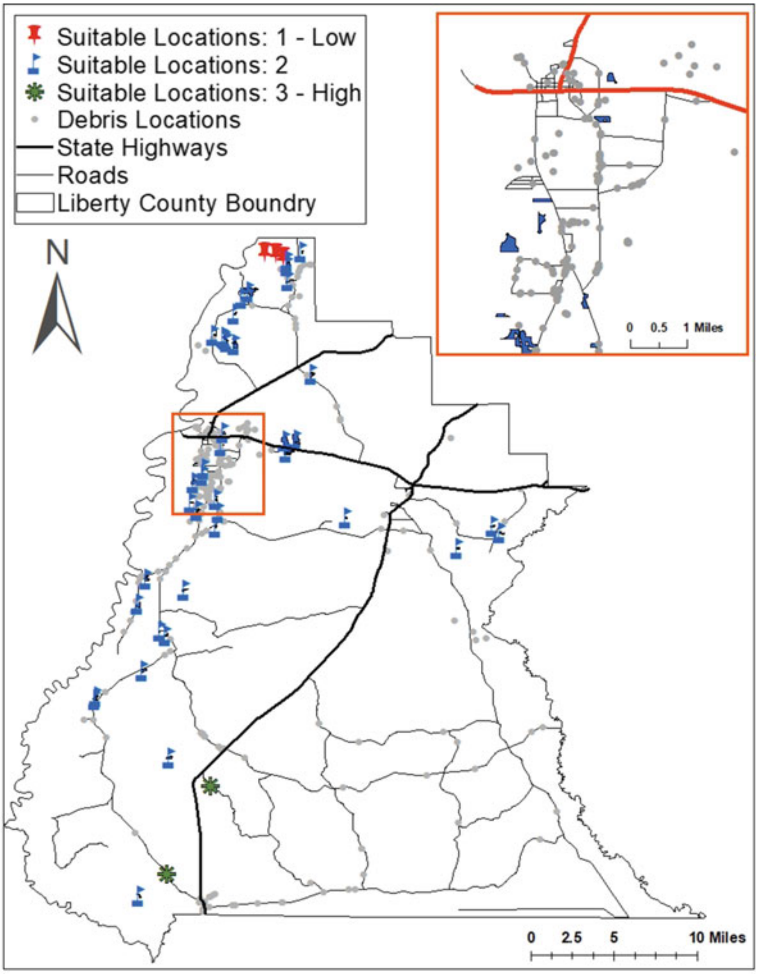

Fig. 4 Suitable locations for TDMS in Leon County, Florida

number of iterations should be tuned to give the optimization engine enough opportunity to search the search space sufficiently. In this regard, the optimization was conducted using various iteration numbers [8000, 9000, 10,000, 11000]. The iteration parameter was set to 10,000 since the objective function's improvement beyond this number was insignificant. Figure 5a shows the normalized value of the best objective function over iterations. As shown in the figure, the objective function drops fast at the early iterations as the algorithm searches globally within the search environment. However, its decreasing rate gradually diminishes as it searches locally and close to near-optimum solutions. According to the figure, the optimization module can successfully explore the search environment and find better solutions as it iterates.

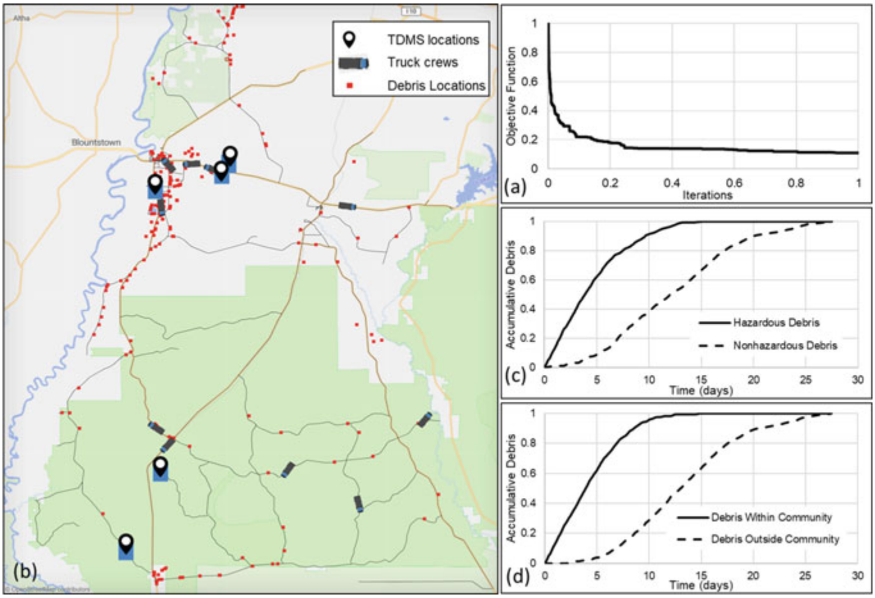

Fig. 5 Optimization Module results: **a** normalized objective function with respect to the normalized number of iterations, **b** the optimum locations of TDMSs, **c** normalized accumulative hazardous debris delivered to TDMSs comparing to nonhazardous debris, **d** normalized accumulative debris located within urban communities delivered to TDMSs comparing to debris outside urban communities

Figure 5b depicts the five optimum locations selected for the TDMSs. Three of the locations were selected closer to urban communities to expedite the debris collection from these communities. All these three sites were ranked "two" (i.e., average) based on suitability analysis. On the other hand, the optimization algorithm selects the two most suitable locations (i.e., ranked "three" according to suitability analysis) in the southern half of the county to manage debris from that region.

Figures 5c, d demonstrate the performance of the optimization module in planning the debris collection process with respect to the debris type and location. In this regard, the model simulates the optimal debris collection operation (i.e., with the optimum TDMS sites and truck routing information) and records the debris delivered to each TDMS over time. Figure 5c shows the total debris delivered to TDMSs with respect to its type. The results show that the optimization algorithm successfully prioritized the collection of hazardous/perishable debris over the others. In this regard, the total duration of collecting hazardous debris was about 50% of the duration of collecting other types of debris (~27 days), although the volumes are the same. Figure 5d shows the debris removal processes for community areas versus non-community areas. The results show that all of the debris located within communities was collected in half the time spent collecting the debris outside urban communities, despite the similar volume of debris in both areas.

4 Conclusions

In this paper, we developed a simulation-based framework, which considers both geographical criteria and post-disaster operations to identify optimum TDMS locations. The proposed framework enables decision-makers to find the optimum TDMS locations as well as truck routing schedules in a way that minimizes not only the overall debris collection time but also health threats to communities. The proposed framework was tested using a case study of debris removal operations for Liberty County, Florida, in response to a hypothetical hurricane event. The results show that the framework successfully identified the most suitable TDMSs considering the volume, location, and type of disaster debris and resulting debris operations. Additionally, the proposed optimization framework identified the truck routing schedules, which effectively collect hazardous debris and the debris located in communities within a reasonable time frame, thus minimizing the health and safety threats. The framework provides a simulation model of post-disaster debris operations with animation, which facilitates decision-making processes by visualizing the overall operations, detecting system deficiencies, and allowing the exploration of various operational scenarios for improvement. The proposed framework is scalable, adaptable, and flexible to facilitate decision-making regarding the location of TDMSs before or immediately after a disaster event. In this regard, the framework is not limited to any specific geographical area, and the same suitability analysis model can be employed to identify suitable locations for TDMSs in other areas. Similarly, the decision-makers can adjust other framework inputs, including resources and debris estimations, according to their available resources and disaster scenario. Additionally, the agent-based-modeling approach enables decision-makers to adjust each agent's behavior (e.g., truck capacity, speed, loading time, unloading time) or add and remove agents to better represent the decision-making scenario of their interest. Finally, the metaheuristic-based optimization engine allows decision-makers to find near-optimum TDMS locations and truck routing schedules in complex problems (i.e., NP-hard) in reasonable computational time.

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Feasibility of Wearable Heart Rate Sensing-Based Whole-Body Physical Fatigue Monitoring for Construction Workers

G. Lee, S. Lee, and G. Brogmus

1 Introduction

The construction industry is one of the most physically demanding occupations. Therefore, physical fatigue, a temporary physical inability to perform optimally [13], is frequently observed among construction workers, contributing to undesired outcomes such as injuries, illnesses (e.g., cardiovascular and heat illnesses), accidents (e.g., struck-by vehicles and equipment), and low productivity [19, 20, 34]. According to the [40], 25.2% of occupational injuries and illnesses involving days away from work in the construction industry were related to physical fatigue and overexertion. To monitor and manage the workers' physical fatigue, current practices have been depending on workers' self-reporting using questionnaires such as the Fatigue Severity Scale [21], the Fatigue Assessment Scale [24], the Occupational Fatigue Exhaustion Recovery scale [43], and the Swedish Occupational Fatigue Inventory [2]. These survey-based measurements enable us to understand the general level of physical fatigue of each individual worker. However, these surveys are conducted sporadically and require workers to stop their ongoing work to participate. Such approaches, therefore, might be limited in understanding the dynamics of physical fatigue during ongoing work, which is essential for making timely on-the-spot interventions before undesired consequences actually happen due to prolonged physical fatigue.

To overcome the limitations, there have been research efforts to continuously and less-invasively monitor workers' physical fatigue during their ongoing work. For

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example, wearable electromyography (EMG) sensors have been widely applied [10, 16] because fatigue on muscles can present as abnormal patterns in electrical impulses produced by muscles during contraction [31] and EMG sensors can detect these abnormal patterns. Recently, a system dynamics (SD)-based muscle fatigue model has been introduced which estimates physical fatigue in dynamic work conditions without attaching EMG sensors to workers' skin, which can be cumbersome to workers given their active body movements during ongoing work [17].

However, most of these previous efforts have focused on localized muscle fatigue which is only one category of physical fatigue. Physical fatigue can be categorized into two: localized muscle fatigue and whole-body fatigue (WBF) [12]. Both types of physical fatigue are commonly observed during construction tasks and are therefore equally important to manage in order to prevent fatigue-related undesired outcomes at construction sites [5]. Localized muscle fatigue occurs when physical activity involving a specific muscle group is repetitive with severe intensity, thereby focusing physical exertion on the specific muscle group. On the other hand, WBF is observed when a worker has engaged in a demanding whole-body physical activity for a prolonged period of time. Under this condition, fatigue substances (e.g., phosphate and lactic acid) accumulate in plasma and WBF occurs as a defensive neuro-physiological mechanism to maintain homeostasis of the body's system [39]. Consequently, during WBF the human central nervous system reduces levels of bodily activation, thereby decreasing workers' alertness—slowing down their perception and cognition. If workers continue physically and cognitively demanding tasks while experiencing WBF, their ability to properly react to surrounding hazards at construction sites is decreased, potentially leading to injuries and loss [1].

Recently, a couple of studies have proposed several wearable biosensor-based methods to continuously and less invasively monitor workers' WBF [5, 23]. Their fatigue monitoring methods detect increased physical exertion as a symptom of physical fatigue given that when workers get fatigued, they might perceive more physical exertion during physical activity. In line with this, these methods were validated using Borg's perceived exertion scale [7] developed to measure physical exertion, not physical fatigue. However, the level of physical exertion does not always coincide with the level of fatigue. For example, while a worker takes a break after a physical activity that was prolonged enough to elicit excessive WBF, they might experience a high level of WBF but not perceive any exertion. Inversely, while starting a physical activity with an extremely high physical demand, they might perceive a high level of physical exertion but not yet experience WBF. In this regard, there is a need for a continuous and minimally invasive monitoring method, not dependent on measuring physical exertion, that can truly track workers' WBF.

The critical power (CP) model [27], a physiological bioenergetic model widely applied in sport science, could provide a theoretical background to continuously track the WBF during workers' ongoing work. The CP model was first introduced by [26] to explain the relationship between the level of power intensity (PI) [kJ/min] and corresponding time [min] to physical exhaustion in a single muscle group. This model has since been extended to whole-body physical activities [27]. This model assumes that there are two energy supplies for human physical activities: aerobic and anaerobic supplies. It is also assumed that aerobic energy's supply capacity [kJ] is unlimited but that its rate is limited, while anaerobic work capacity [kJ] is limited but is not rate-limited. Here, the rate limit of aerobic work is called critical power (CP). Therefore, when PI is less then CP, the aerobic supply's rate limit, we can theoretically expect that the person can continue the ongoing physical activity infinitely depending on their aerobic supply. On the other hand, when the PI is more than the CP, the physical activity requires the use of anaerobic energy supply. Since anaerobic work capacity is limited, if the physical activity continues, the person eventually uses up all their anaerobic work capacity and ends up being physically exhausted. Here, the level of WBF can be expressed as the proportion of expended anaerobic work capacity (AWC_{exp} [kJ]) over its total capacity (AWC_{tot} [kJ]) (Eq. 1) [42] and physical exhaustion is defined as 100% WBF where anaerobic work capacity is totally depleted. The time to physical exhaustion (T) [min] can be calculated from AWC_{tot} and a constant PI and CP using Eq. 2.

$$\text{WBF}[\%] = \text{AWC}_{\text{exp}}/\text{AWC}_{\text{tot}} \tag{1}$$

$$T = \text{AWC}_{\text{tot}}/(\text{PI} - \text{CP}) \tag{2}$$

Beyond constant PI scenarios, the CP model can be also applied to physical activities with variable PI, which suits most actual cases [28, 37]. In these cases, the increase of AWC_{exp}, accompanying the increase in WBF, can be tracked by integrating the PI minus CP over time. In other words, while AWC_{exp} accumulates during moments when PI minus CP is positive, AWC_{exp} stays or dissipates during moments when PI minus CP is zero or negative. Equation 3 describes this relationship between PI, CP, and AWC_{exp}.

$$\frac{\text{dAWC}_{\text{exp}}(t)}{\text{d}t} = \begin{cases} \text{PI} - \text{CP}, \ \text{PI} - \text{CP} \geq \text{AWC}_{\text{exp}}(t) \\ -\text{AWC}_{\text{exp}}(T), \ \text{PI} - \text{CP} < \text{AWC}_{\text{exp}}(t) \end{cases} \tag{3}$$

The value of AWC_{exp}, the amount of expended anaerobic work capacity, does not go down to a negative value inherently. Accounting for this, Eq. 3 describes the AWC_{exp} change per unit of time with two conditional expressions as follows. Using Eq. 3, along with Eq. 1, the workers' WBF can be continuously tracked as shown in Fig. 1 if we can continuously measure the PI and know the value of CP in the activity context [37]. However, there is a hurdle in applying the CP model to measure the WBF in workplaces. Unlike sport exercise where PI can be relatively easily measured by observing the output performance of repeated activities such as a running and cycling pace, in a workplace it can be challenging to continuously monitor variable PI during tasks that are less repeated and involve diverse forms of physical activity. Though several previous studies have proposed and applied very similar models with CP model to monitor workers' WBF [9, 30], they have not suggested a practical way to track variable PI in workplaces, which is essential for their models' WBF monitoring.

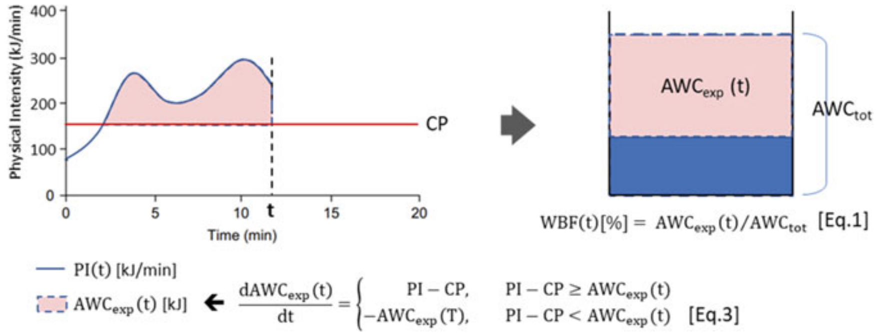

Fig. 1 CP model-based WBF measurement from monitored physical intensity

Recent advancements in wearable biosensing has opened the door to continuous and minimally-invasive monitoring of workers' PI trends during their ongoing work. Specifically, the percentage of heart rate reserve (%HRR) [6], which can be continuously measured by most off-the-shelf wristband-type biosensors, has proven to be a useful indicator of workers' PI under diverse dynamic physical work environments including construction [14, 18, 35]. %HRR and PI are linearly associated between 0% and 65%HRR [11] which covers most physical activities taking place in occupational work contexts [15, 44]. Although other mental factors such as emotions can also affect %HRR, PI is the most dominant factor influencing HR changes in the long term [14, 18]. Therefore, %HRR might be useful in tracking WBF using the CP model over a relatively long term such as an hour or a day [14], which this study aims to do.

Despite the potential for understanding WBF in workplaces by integrating wearable %HRR monitoring with the CP model there has been little study in this area. Although several studies based on CP or similar concepts (e.g., anaerobic threshold) have suggested a general upper limit on PI as a %HRR value to keep workers from spending their anaerobic work capacity, thereby preventing the WBF accumulation [44], to the authors' best knowledge there has been no attempt to continuously measure workers' WBF by combining wearable biosensing and the CP model. To fill this gap in our knowledge, this study proposes a wearable heart rate sensing and CP model-based WBF monitoring method to test its feasibility in a real construction work setting—one of most physically demanding and dynamic work environments.

2 Proposed Whole-Body Fatigue Monitoring

Figure 2 describes an overview of the proposed method to monitor workers' WBF during ongoing work. First, workers' heart rate (HR) is continuously measured using an off-the-shelf wristband-type biosensor. From this measured HR, %HRR is calculated as an individual PI index (Fig. 2a). Then, the CP model is applied to monitor

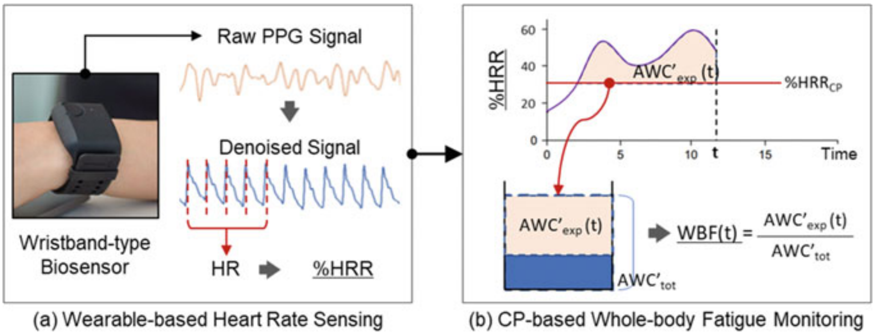

Fig. 2 Overview of the proposed wearable heart rate sensing and CP model-based whole-body fatigue monitoring method

WBF from the calculated %HRR (Fig. 2b). The following two subsections will describe each step in more detail.

2.1 *Wearable-Based %HRR Monitoring*

To monitor workers' HR, the authors applied an off-the-shelf wristband-type biosensor that can continuously measure photoplethysmogram (PPG) on wrist skin. PPG is an optical signal that is acquired by illuminating skin and measuring changes in the skin's light absorption, reflection, and scattering [41]. Changes in the absorbed or reflected light are detected by a photodetector and used to measure the volumetric flow of blood beneath the target skin area. Since the main factor modulating volumetric blood flow is cardiovascular activity, PPG has been widely applied to monitor heart activity-related metrics such as HR and heart rate variability [22]. The collected continuous PPG signal is segmented every minute. In this study, the unit of time in the WBF monitoring was set by a minute like previous studies measuring heart rate as an index of physical intensity [4, 33]. This is to limit the impact of acute mental status alteration on the %HRR monitoring while having an appropriate granularity. After removing baseline wandering using a median filter, empirical mode decomposition was applied to extract heartbeat-induced components whose frequency is between 0.8 and 3.3 Hz. By combining the extract components, the heartbeat-induced-intensity variation (HIIV) was reconstructed and, then, HR was calculated by counting the HIIV's peaks. As an individual PI index, %HRR is calculated from the HR. To convert HR to %HRR using Eq. 4, each subject's maximum HR (HR_{max}) is calculated by applying Eq. 5 [38], and resting HR ($HR_{resting}$) can be measured during the subjects' break time.

$$\%HRR = \left(HR_{working} - HR_{resting}\right) / \left(HR_{max} - HR_{resting}\right) \quad (4)$$

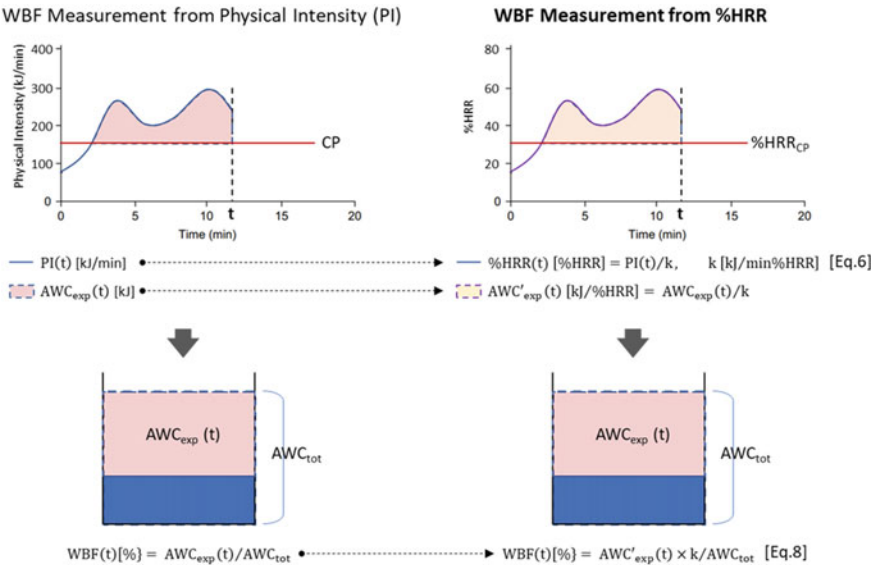

Fig. 3 WBF monitoring from %HRR instead of physical intensity using CP model

$$HR_{max}[\text{beat/ min}] = 208 - 0.7 \times \text{Age}[\text{yr}] \tag{5}$$

2.2 CP Model-Based WBF Monitoring

Figure 3 describes how WBF is measured from %HRR instead of PI by applying the CP model. Equation 6 in Fig. 3 represents the linear association between PI and %HRR by introducing a constant k [kJ/min per %HRR] that basically indicates the unit PI per %HRR. Using the constant k, an index of AWC_{exp} (AWC'_{exp} [kJ/%HRR], which is AWC_{exp}/k) can be expressed as a function of %HRR (Eq. 7). To calculate AWC'_{exp} by Eq. 7, the %HRR at CP ($\%HRR_{CP}$, which is CP/k), the threshold on the %HRR dimension determining whether fatigue is accumulating or not, first needs to be determined. According to previous studies into maximum allowable workload [25, 29, 30, 44], the $\%HRR_{CP}$ can be determined between 20%HRR and 33%HRR in occupational contexts. With this background, a feasibility study calculated AWC'_{exp} by changing $\%HRR_{CP}$ from 20%HRR to 33%HRR in increments of 1%HRR. Once AWC'_{exp} is calculated, WBF on percentage is computed by multiplying the AWC'_{exp} and k/AWC_{tot} (Eq. 8). Since the constant k and AWC_{tot} vary among individuals according to their personal characteristics such as age, weight, height, and other health conditions [8, 36], the k/AWC_{tot} needs to be individually estimated for measuring WBF. Basically, the term k/AWC_{tot} is the slope of the linear relationship between the WBF and AWC'_{exp} calculated from %HRR so we can estimate individuals' k/AWC_{tot} by observing actual WBF and %HRR multiple times and conducting a linear regression modeling between WBF and AWC'_{exp}.

$$\%HRR(t)[\%HRR] = PI(t)/k,\ (k[kJ/\min\%HRR]) \tag{6}$$

$$\frac{dAWC'_{exp}(t)}{dt} = \begin{cases} \%HRR(t) - \%HRR_{CP},\ \%HRR(t) - \%HRR_{CP} \geq AWC'_{exp}(t) \\ -AWC'_{exp}(t),\ \%HRR(t) - \%HRR_{CP} < AWC'_{exp}(t) \end{cases} \tag{7}$$

$$WBF(t)[\%\} = AWC'_{exp}(t) \times k/AWC_{tot} \tag{8}$$

Feasibility Test

This feasibility study focuses on examining whether the AWC'_{exp}, the index of AWC_{exp} calculated using %HRR and CP model, has a linear association with the WBF prior to individual regression modeling. The authors collected two days of field data from 12 construction workers in a construction site located in Ann Arbor, Michigan. This site was selected because a new construction and a renovation were in progress together at the site, which was good to test the proposed monitoring method with workers of various trades and diverse work environments. The field data collection was conducted for 11 days from the end of August 2019 to the middle of September 2019. Table 1 shows a summary of the demographic information of the 12 subjects. Specifically, the subjects' PPG signals were collected using a wristband-type biosensor during their ongoing work. At the same time, the authors asked the workers to verbally rate their perceived WBF using the Swedish Occupational Fatigue Inventory scale (SOFI) [3] that has been widely used to survey the WBF over a relatively short time scale such as an hour among diverse occupational contexts. The SOFI is easy to follow; it asks four questions on a scale from 0 to 6 and averages subjects' responses to measure the WBF. The fatigue survey was conducted up to three times a day between 9 AM and 3 PM over a two-hour interval with minimal interference with their work. The field data collection protocol was approved by the University of Michigan Institutional Review Board.

Table 1 Summary of the subjects' demographic information

	Age (years)	Job experience (year)	Height (cm)	Weight (kg)
Mean	38.3	14.5	180.3	95.8
Standard deviation	12.0	11.4	6.8	11.4
Minimum	20	0	163	76
Maximum	60	31	191	113

From their collected PPG, the authors measured workers' %HRR and AWC'$_{exp}$ every minute. AWC'$_{exp}$ was calculated by changing %HRR$_{CP}$ from 20%HRR to 33%HRR in increments of 1%HRR. Then, the Pearson correlation coefficient between the calculated AWC'$_{exp}$ and the workers' perceived WBF was examined to see the association between the two variables as an index of feasibility of the proposed monitoring method. Before calculating the correlation coefficient, we first standardized both AWC'$_{exp}$ and perceived WBF by individual to take account for the different slope (k/AWC$_{tot}$) between the two variables among subjects.

3 Result and Findings

Through the field data collection, a total of 175 h of PPG signals were collected (14.6 h per each subject) and 66 WBF surveys were conducted (3 to 6 observations per each subject). As a result of correlation analysis, the highest correlation coefficient was 0.61 (p-value $\approx$ 0) when %HRR$_{CP}$ was set at 26%HRR. This correlation coefficient shows that the AWC'$_{exp}$, calculated by applying wearable HR sensing and the CP model, is strongly correlated with workers' perceived WBF. Specifically, these results can be interpreted as very promising given that applying individualized %HRR$_{CP}$ can bring a much higher correlation coefficient because all 12 subjects conducted different tasks (e.g., rebar carrying, installation, form work, etc.) with different groups of muscles' involvements [42].

This promising result indicates that the proposed monitoring method is feasible to track the changing trend of a worker's WBF. However, to measure WBF on percentage and ultimately manage it not to reach its 100% (i.e., physical exhaustion) in practice, the slope of the linear relationship between the AWC'$_{exp}$ and WBF on percentage needs to be further determined individually. As a preliminary trial, the authors picked one subject who showed the most variable physical intensity during his work and determined his slope value (i.e., k/AWC$_{tot}$) by conducting a linear regression modeling using his six WBF surveys. Using the determined slope value, his daily WBF was visualized as shown in Fig. 4. The figure demonstrates that the physical intensity (PI) and the WBF trends do not always coincide. For example, at around 9:30 AM, the worker's PI is relatively low (around 20%HRR) but his WBF is relatively high (around 35% WBF) because although at that point he was doing a physically easy task (walking with a light material), he had just previously conducted a physically demanding rebar carrying task. This difference between PI and WBF might not have been detected by the previous physical exertion-based WBF monitoring methods.

The result of this feasibility study shows the promising association between the index of WBF calculated by the proposed monitoring method (AWC'$_{exp}$) and the workers' perceived WBF. Therefore, in a future study, the authors intend to examine how to practically determine the individual slope between AWC'$_{exp}$ and WBF, thereby tracking individual WBF on percentage. Collecting blood samples and measuring fatigue substance accumulation in the samples are the gold standard for the

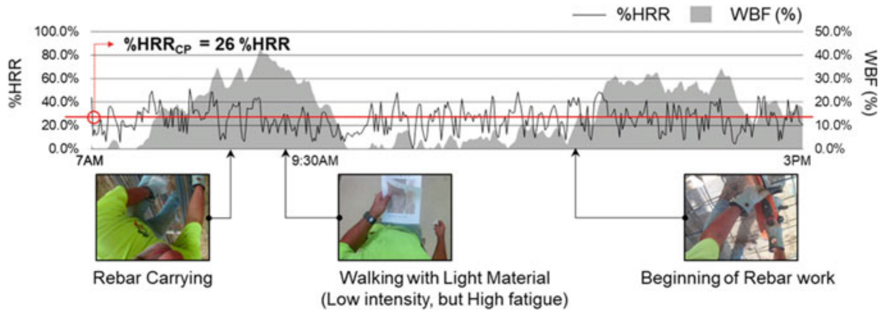

Fig. 4 Daily trend of %HRR and the whole-body fatigue (subject #3)

WBF measurement. However, because the blood sampling-based fatigue measurement is too invasive to be used in the workplace, manually surveying workers' perceived WBF using a questionnaire (e.g., SOFI) might be more practical. Then, the minimum number of perceived WBF surveys for reliable regression modeling and WBF monitoring should be determined. Whether the individual slope between AWC'_{exp} and WBF can be predicted based on each individual's demographic and physiological variables (e.g., age, job experience, trade, body mass index) should be investigated in a future study as well to advance the field applicability of the proposed monitoring method. Also, although this study shows a promising correlation between AWC'_{exp} and WBF using one fixed $\%HRR_{CP}$ value (26%HRR), if $\%HRR_{CP}$ is determined individually accounting for each worker's personal characteristics and work contexts, it must significantly advance the performance of the proposed WBF monitoring. Therefore, how to determine individual $\%HRR_{CP}$ also needs to be examined in future research. In addition, although workers' mental factors' (e.g., stress and emotion) impact on %HRR might be limited in the long term [14, 18], how these factors affect the proposed WBF monitoring method's performance still needs to be exmined in future studies.

4 Conclusion

Although there have been many research efforts to apply wearable technologies to continuously and non-invasively monitor workers' physical fatigue during their ongoing work, most of these efforts have focused on localized muscle fatigue rather than the whole-body fatigue (WBF)—an important type of physical fatigue that is closely related to workers' safety, health, and productivity. To extend the application of wearable biosensors to monitoring WBF, the authors proposed a monitoring method that applies wearable heart rate sensing and the critical power model together. A feasibility test was conducted using data collected from 12 workers at a construction site. As a result, the index of expended anaerobic work capacity (AWC'_{exp}) calculated based on the measured heart rate and critical power model showed a significantly high correlation coefficient with workers' perceived WBF. This result indicates that the proposed method is feasible to continuously track the trend of workers' WBF during ongoing work. The finding of this study can contribute to understanding construction workers' WBF during their ongoing work, thereby helping us to prevent WBF-related detrimental outcomes such as physical exhaustion, distraction, and slow perception and cognition of surrounding hazards at job sites. Specifically, given that most affordable wristbands include heart rate monitoring capacities, the proposed method is expected to be easily applicable in real construction practice.

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Improving Project Definition Practices with Lean-Led Design

Hafsa Chbaly, Daniel Forgues, and Samia Ben Rajeb

1 Introduction

Defining and formalizing clients 'requirement into design solution is challenging and difficult in healthcare projects due to three reasons. The first one is related to the project complexity. In fact, there are a large number and a wide diversity of clients: users (patients, staff, families), funders (government or insurance companies), members of the public and managers/decision maker. Each client has his own needs that could be in some cases conflicting with other clients' stakeholder needs [12]. Further, healthcare facilities represent a complex interaction of various elements, such as building services, equipment, and other components [11]. The second reason is the dynamic environment of healthcare projects. The needs are constantly evolving due to changes in demand, aging population, advances in healthcare processes or rapid expansion of technologies [9]. The third reason is the large number of regulations that control the design of healthcare services [11]. A poor project definition could have a significant impact on patient health and recovery and on clinicians' wellness and safety [22].

For these reasons, design professionals need to better understand the users' needs to better define the project and thus deliver buildings with a better fit for use or purpose [26]. However, traditional project definition practices proved to be inadequate [3, 9]. The focus of the design professionals is more on the technical issues rather than the functional ones [14]. They usually do not have enough knowledge about users and how they perform the services in the hospital [4]. This leads to alignment

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problems between what the architects propose, as a spatial solution, and the optimal configuration to clinical activities.

One of the solutions proposed to deal with that is Lean-led Design participative approach Grunden and Hagood [10]. Unlike the traditional project definition approaches, in Lean-led Design the users are not regarded as passive recipients of services. They play a significant role from the beginning of the project [11]. The focus of Lean-led Design approach is on analyzing and optimizing the care pathways: determining how to best meet the users' needs and how to facilitate the smooth patient flow. This facilitates the development and the evaluation of the best design options for the users.

Lean-led Design has gained popularity in United Kingdom and in America [9, 24]. It was implemented in different hospitals such as Virginia Mason Hospital in Seattle, and Sunny Hill in British-Columbia. This participative approach should afford better efficiency and quality of services, minimize costs, improve patient safety and avoid future operation and construction problems [11]. Lean-led Design is increasingly recognized for the project definition of healthcare facilities. Yet, there is still a little research on this subject and results of applying this approach are limited [22].

This paper sought to address the following questions: What is known from the existing literature about Lean-led Design approach? And what are the expected benefits of the approach? To do so, a mixed method based of a scoping review [18] with semi-structured interviews were carried out. Section 2 describes the methodology used to answer the questions raised. Section 3 presents the results obtained in terms of terminologies, definitions, methods/techniques of Lean-led Design approach, and the main impact of Lean-led Design in the project definition process. The final section discusses and concludes the paper presenting the main ideas and proposing future research directions.

2 Methodology

To answer the aforementioned research questions, this research was realized in two steps: (1) scoping (literature) review and (2) interviews.

The first step represents a scoping review. It aims to answer the first question: What is known from the existing literature about Lean-led Design approach? Scoping review is used to identify research gaps in existing literature, to provide an overview or map of the evidence and to highlight directions for further research [2, 18]. Inline with guidelines proposed by Arksey and O'Malley [2], this scoping review followed different steps after identifying research questions: identifying relevant studies, selecting the ones for a full-text review, summarizing and reporting results.

Relevant studies were retrieved by searching in two databases relevant to the topic: google scholar and Scopus. Using the keywords: ("Lean-led Design" OR ("Lean" AND "project definition" AND ("hospital" OR "healthcare"))), a total of 73 articles were identified. The initial search was focused on the abstract, title and author's keywords of the publications. After that were selected: (1) studies published in peer-reviewed journals, doctoral theses, conference papers and research reports between 2012 until 2021, (2) documents with full text available, (3) papers in the construction industry focusing on hospitals, (4) papers in English, French or Spanish because of our expertise in these languages. Thus, the number of publications decreased to 18, which correspond to the final number of publications retained for this study.

The second step represents the interviews. The objective was to answer the second research question: What are the expected benefits of the approach? To do so, 20 semi-structured interviews were conducted between 2018 and 2020. All interviewees had implemented Lean-led Design methods or participated at least once to its implementation during the project definition of a mega Canadian hospital: Lean facilitator, project managers, clinical managers, design professionals, clinicians. The duration of the semi-structured interviews was on average between 60 and 75 min. These data were transcribed and coded with the qualitative data analysis tool NVivo, to unveil the main themes of the participants' testimonies which helped us to develop a comprehensive view of the main impact of Lean-led Design in hospitals.

The next section presents the results.

3 Results

This section is structured in two parts. First, the results of our scoping review about Lean-led Design are detailed: terminologies, definition, methods and techniques (3.1). Secondly, the main themes that emerged out of participants' testimonies are described (3.2).

3.1 Results of Scoping Review

3.1.1 Different Terminologies of Lean-Led Design

Even though there are a few papers on this subject, the terminologies used by the authors are diverse. After analyzing the articles, we have identified a lack of consensus on a "Lean-led design" terminology. In fact, seven different terminologies were found: Lean-led design (e.g., Grunden and Hagood [10], Lean healthcare Design (e.g., Raijula et al. [20], Lean 3P design (e.g., Hicks et al. [12]), Lean Design of hospitals (e.g., Hicks et al. [11], Lean exploration loops into healthcare facility (e.g., Mazur et al. [16], Lean-led architectural Design (e.g., Ding [7], and Lean-led hospital Design (e.g., Vizient 2019), (Table 1).

The authors mostly use two different terminologies as synonyms. As an example, Hicks et al. [11], treated Lean 3P Design and Lean Design of hospitals as the same terminologies. The term "Lean-led Design" is used in the current paper since it is the most widely used term in the literature to describe our concept of interest.

Table1 Different "lean-led design" terminologies

Terminology	Authors		N.A
Lean-led design	(1) Grunden and Hagood [10] (2) Forgues et al. [9] (16) Pennington-Block et al. [17]	(3) Phiri and Chen [19] (4) Schouten et al. [22]	5
Lean healthcare Design	(5) Reijula et al. [20] (6) Van Amstel et al. [27] (17) Van Amstel et al. [27]	(15) Reijula et al. [21]	4
Lean 3P Design	(7) Hicks et al. [12] (8) Hicks et al. [11] (9) Smith et al. [24]	(10) Smith [23] (11) Smith [25] (18) Coletta [6]	6
Lean Design of hospitals	(8) Hicks et al. [11]		1
Lean exploration loops into healthcare facility	(12) Mazur et al. [16]	(13) Johnson et al. [13]	2
Lean-led architectural design	(14) Ding [7]		1
Lean-led hospital design	(1) Grunden and Hagood [10]	(4) Schouten et al. [22]	2

Furthermore, although there is no consensus in the terminology used, there is a consensus about the stages where this approach could be implemented and Lean-led Design definition.

3.1.2 Lean-Led Design: Its Implementation and Definition

The majority of the authors would agree that the Lean-led Design approach should be used during the whole project definition, i.e., during the planning, programming and schematic design stages [1], (Table 2). The first stage (planning) refers to the identification of the client's needs, the second (programming) to the definition of a functional and technical program including a detailed space program and the last (schematic design) as the first architectural concept.

Lean-led Design exists in the literature since 2012. Few authors have presented a definition of this approach (Table 3); however, those who have done, often used that of Grunden and Hagood [10]. It means that there seems to be a consensus regarding the definition unlike the terminology, among the researchers in the field.

According to the definition provided by Grunden and [10], Lean-led design is a participative approach specific to hospitals. It aims to improve the organizational effectiveness and patient well-being in healthcare projects. Definitions proposed by Ding [7] and Reijula et al. [20] are in line with the previously mentioned definition but with an emphasis on the point that not only it is a participative but also a user-centric approach. Unlike the traditional approach in which the architect is in the lead, in the Lean-led design the emphasis is on the patients with a focus on physical environment. The objective is to rethink the ways hospitals works and to align the

Table 2 Lean-led design implementation

		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)
Project definition	Planning	•	•	•	•	•	•	•		•	•				•	•		•	
	Programming	•	•	•	•		•	•		•	•		•		•	•		•	
	Schematic design	•	•	•	•			•		•	•			•		•		•	

Table 3 Lean-led design definition

Definition	Principal author of the definition	Authors using the same definition
"It is a systematic approach to healthcare architectural design that focuses on defining, developing, and integrating safe, efficient, waste-free operational processes in order to create the most supportive, patient-focused physical environment possible"	Grunden and Hagood [10], p.18	Hicks et al. [11]
		Pham et al. [18]
		Ding [7]

real users 'needs, including those of the patient, with the design solution. In order to achieve this objective different methods and techniques were proposed.

3.1.3 Methods and Techniques

Different methods and techniques have been proposed by researchers in the field to implement Lean-led Design (Table 4).

All of these methods/techniques are adapted from or inspired by Lean production. They have often been explained in the literature [10, 20]. Furthermore, there is a consensus among researchers that these methods and techniques have two ultimate goals: minimizing waste and generating value for the client during the process of project definition.

On one side, minimizing waste is linked, in hospitals, to the improvement of seven types of flows: patients, staff, visitors, supplies, equipment, medication and information [12]. Unlike the traditional approach that starts with an estimate of the required area of each department, in Lean-led Design approach, the focus is on optimization of different flows and improving the services of the hospital before calculating the required square meters. In other words, before looking for an architectural solution, we had to question all the ways of doing things in the different times that we live in Hicks et al. [11]. To do so, authors proposed methods /techniques such as Value Stream Mapping (VSM), 5S or Genchi Genbutsu [10, 24].

On the other side, in order to provide the best layout to conduct clinical activities, authors propose the involvement of the users in different participative activities such as *kaizen* or 3P, during the whole process of project definition. While defining patient/client value creation is not an easy task, authors such as Grunden and Hagood [10], Hicks et al. [11] have argued that practical workshops involving the participation of future users facilitated the conceptual design phase of construction projects. In fact, the architects have insufficient knowledge of hospital work process from the arrivals of different types of patients until their departures [21]. Thus, users' involvement should help to raise awareness about the users' reality, needs and certain issues that were not obvious at first to professional teams.

Table 4 Lean-led design methods/techniques

Method/Technique	Objective	Related Work
Kaizen workshop	"Looks closely at processes or problems, analyzing how they arose, and uses the wisdom of the team to devise experiments and improve them" (1), p. 52	(1), (8), (2)
3P Workshop	3P (product, process, preparation) " affects the processes, systems and everyday activities that people will improve on an ongoing basis" (1), p. 52	(1), (8), (2), (12), (7), (10)
Value stream mapping (VSM)	Flow mapping in order to eliminate non-value-added activities and optimize the logistics inside the health-care facility	(1), (2), (9), (4)
5S	Means: Sort, Set in Order, Shine, Standardize, Sustain. The objective is to eliminate different waste [5]	(1), (8)
Standardization	"By standardizing work processes, Lean enables a relatively steady and predictable work process delivery flow, which leads to more efficient hospital space usage" (5), p. 177	(1), (5), (3)
Visual management	"Provides an effective way for all health-care professionals to learn and store information" (5), p. 5	(1), (5), (12)
Genchi Genbutsu	"Going to the source of information to find the relevant facts and to make correct decisions. This is a key concept in Lean and in short it means finding the source of error and fixing it" (5), p. 6	(5)
Mock-ups	Full-scale mock-up are used in order to test the different options for the design. Mock-ups facilitate are also used to facilitate for the users the understanding and the visualization of the space designed	(1), (8)

Next, the expected benefits of the implementation of Lean-led Design methods and techniques during the project definition are presented.

3.2 Expected Benefits of Lean-Led Design

The expected benefits of the implementation of Lean-led Design were raised by the respondents. These respondents were involved in the project definition process of a mega-hospital in Canada that implemented Lean-led Design. This mega-hospital represents the consolidation of the activities of two hospitals on the site of the former. The merger appeared as a unique opportunity to create a hospital thought for the patients and around their needs, while there were obvious issues regarding the harmonization of current care and services delivered by the two hospitals. The use of the Lean-led Design approach by the project team aimed to encompass a systemic thinking to collect requirements from all stakeholders, putting the emphasis on relation between clinical services. A Lean-led Design model was implemented through *Kaizen* activities that marked the different stages of the project definition. From May 2014 to November 2016, seven *Kaizen* activities have been organized with the participation of the clinicians, patient, clinical managers, project managers, design professionals. Those *Kaizen* were designed to develop a common vision among various users mobilized in the project.

Thus, based on the implementation of those *kaizen*, three mains expected benefits were raised by the interviewees: reducing complexity, effective care, and sense of ownership.

- **Reducing complexity**

The majority of the respondents agreed with the fact that the implementation of Lean-led Design activities reduces the complexity of defining the needs of the hospital project and also fostered an effective needs-defining process for dialogue and communication with a wide range of clients including users of the two merged hospitals. The mobilization of all hospital sectors facilitates the creation of common vision and thus the reduction of project complexity. As expressed by someone: "I really believe in grouping teams, it creates synergies; it creates the setting of common expertise and thus reduce the complexity of the process." (Lean-led Design facilitator).

By involving different users, the strength of both hospital activities was unified. The participants of the *kaizen* have represented the different flows of both hospitals: movements of patients, staff, medications, materials, and information. This exercise facilitates the unification and the improvement of the hospital trajectories: "having all the stakeholders around the table for discussion, facilitates the understanding of the needs and the constraints of each sector" (Clinician). The different interactions between architects and users not only facilitate the understanding of the different sectors but also made it possible to consider different points of view in order to consider both functional and technical needs, unlike in the traditional approach.

- **Effective Care**

Another impact of Lean-led Design according to the respondents is to get more effectiveness in the care provided. As one participant noted: "So we really want to orchestrate the organization of care and services in the most possible effective way for the patient." (Clinical manager). An added value is perceived by participants as the clinical specialties and professional services were grouped by type of patients, separating the different types of flow in the new facilities. Participants underlined that this new hospital is a unique opportunity to develop consolidated care services for the overall population, and to bring an added value for the patients. However, as denoted by one participant, it was not always easy to translate this general principle into tangible project items: "A big, central theme that came up all the time was the patient at the center of the episode of care, but it has to be declined so that it tells us something. Because it is a great concept, but how are we going to make it happen in our project?" (Clinician). One way to do this was by ensuring that the definition of relevant and excellent care connected to the four missions of the hospital. Another aspect of this was to provide a better care experience for the patients, by offering a welcoming and secure environment along with information that meet their needs. Thus, the patients' trajectory in the future hospital were though so that the experience would be facilitated, for ambulatory purposes and for more fluid care given by professionals concerted and coordinated around their needs.

- **Sense of Ownership**

According to the respondents, one of the advantages of Lean-led Design is the sense of ownership: "I would say that the greatest advantage is the ownership of the project by the clinicians" (project manager). The users develop a collaborative and shared project identity throughout the process of project definition. Starting from a sectoral/hospital perspective to gradually move towards a united "us". As time passed and activities unfolded, the overall synergy of participants were improved, as each got a deeper understanding of the reality of others, as silos and other organizational barriers were broken down via a transversal and collective approach. From many testimonies was expressed satisfaction towards the approach and the outcomes: "The *kaizen* allowed us to debate among clinicians in order to project ourselves in a much more optimal way as a group. The objective is to have a common, clear, and more complete vision of the different services. The *kaizen* also allowed us to better understand the choices and decisions" (Clinician).

However, the involvement of the users impacts their level of expectation: "when the involvement of the users is high, their expectations are high. Thus, the disappointment is great" (Clinical manager). According to the respondents, if the users are not aware that their needs identified during the *kaizen* could be changed during the time, this could lead to their disappointment if their needs are not achieved.

4 Discussion and Conclusion

The goal of this paper was to understand the Lean-led Design approach and to investigate its expected benefits. Through the scoping review, we provided an overview of Lean-led Design. We found several gaps in the literature. First of all, even though

Lean approach has been widely used in the context of healthcare during the operation stage (Lean healthcare), it is rarely used during the project definition specially in complex large-scale hospital and reconstruction project. “Lean-led Design” is a relatively new line of research. Few papers have been published, which limited our study.

Further, from the small body of literature, the existing publications are more aimed at the practitioners (e.g., Grunden and Hagood [10]), thus, they primarily present empirical cases of the application of Lean-led Design and rarely (if at all) address it from a theoretical and scientific perspective. Moreover, even though most of the papers present case studies, their focus is on one specific stage of the project definition or one specific department of a hospital.

Furthermore, during the interviews, the respondents highlighted different benefits of using Lean-led Design. The project definition seeking stakeholders’ involvement facilitates value creation through structural, relational and cognitive network dimensions [15]. When the specialized care units work together, they consciously created a harmonic patient flow. This result is in line with the one of Hicks et al. [11], Grunden and Hagood [10]. Thus, team synergy emerges and strengthens through time, facilitating project definition and focusing on enhanced patient care in the envisioned new hospital.

Healthcare is complex system with multiple stakeholders. The results indicate the importance of the involvement of not only the clinicians and the managers in the process of project definition but also the patients. Their involvement should guide the designers to always keep patient at the center of the process and never lose sight of what is best for him. It should also facilitate the development of care services that go towards the patient and not the other way around. Thus, the close interactions between the design team and the users are required to facilitate the understanding of the hospital operations and the functional space requirements. By involving the users (including the patient) in the process, the designers create more appropriated hospital spaces to the users needs. However, the over mobilization of users could also lead to the loss of focus on project progress and to disappointment if their expectations are not met [8].

Therefore, Lean-led Design empowers users during the project definition. In this approach, the users become a valued team member. They retain the lead in the project definition with the design professionals, which gives them more ownership of the process, unlike in the traditional approach.

This research contributes to enriching our knowledge about the project definition phases of hospitals. It contributes to a better understanding of the alignment issues between users’ needs and design professionals proposed solutions to deliver optimal patient-centred hospitals. It also provides interesting avenues for future research, as there is still a lack of common protocol and steps to follow in order to implement Lean-led Design approach. This research could benefit from an even longer time perspective, as the project will continue, and important insights might be gained through time. As reflexive practitioners are involved in this project, a research-action design could help to get even more fine-grained knowledge in the dynamic processes of stakeholder involvement in projects and their effects of the project and the outcomes.

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The Use of BIM for Robotic 3D Concrete Printing

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1 Introduction

The construction industry is facing serious problems due to low productivity and lack of skilled workers. Digital transformation can be an effective solution to overcome these challenges [18] especially with digital design. BIM and Virtual Design and Construction (VDC) are commonly used for coordination, project management, quality control and project handover. Digital tools offer a variety of functionalities that facilitate the design of innovative structures, but this capacity remains largely underutilized due to the complexity of nonconventional architectures [8]. Concrete construction through additive manufacturing has a strong capability to unlock this innovative potential [14]. This methodology has been proven, in various studies, to offer architecturally attractive projects with economically and environmentally efficient results compared to projects carried out using conventional construction methods [22]. Many of these research projects are limited to studying the material properties and use workflows specific to the field of additive manufacturing. As a result, the adoption of this technology in construction remains ambiguous for designers. In this context, through the visualization of construction data. The use of BIM represents the core of digital transformation in construction since it provides the technological environment necessary for project modeling [18]. Many researchers have assessed that BIM processes contribute significantly to improving productivity throughout the building's life cycle, from design to operation and maintenance

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(O&M). It is a collaborative process that allows users to work in a BIM environment and exchange information through open file formats. Therefore, the integration of BIM-based construction activities with 3DCP can improve the performance of the construction workflow and contribute to the development of the industry.

This research project aims to integrate the two concepts to facilitate the digital shift of the construction industry, but this association faces several interoperability challenges. Interoperability is defined as the ability to exchange information between all software or platforms used by the construction team throughout the project lifecycle [21]. According to Gallaher et al. [6], 107, "$15.8 billion in interoperability costs were quantified for the U.S. capital facilities supply chain in 2002". This concept should not be limited to the technological dimension alone since it also includes an organizational, procedural and contextual dimension [16]. The use of 3D concrete printing within a construction company provokes changes in its organization since this technology implies drastic alterations in work methods [23]. These interoperability challenges persist in both the industry and the academic field. There are few examples of any research that integrates the concepts of BIM and robotic 3DCP in any depth. Thus, this project seeks to clarify the main links between these two technologies, including parametric design.

2 Literature Review

To identify the processes used for applying BIM to robotic 3DCP, a bibliometric analysis is carried out. This analysis uses the systematic literature review (SLR) method to summarize the most relevant articles for the analysis [12]. In addition, the backward and forward snowballing method is used as a support for the SLR to be able to identify articles addressing the subject directly. This analysis is mapped using the VOSviewer software, which visualizes bibliometric maps [20]. The generated map is based on bibliographical data of the SLR output, it has a co-occurrence as a type of analysis and the authors' keywords as a unit of analysis. The minimum number of co-occurrences is set at two, resulting in 34 co-occurring keywords grouped under eight clusters. Figure 1 shows the authors' co-occurring keywords in the literature review articles. Terms with a higher number of occurrences are displayed in larger font, and the line thickness represents the number of items in which all related terms appear simultaneously.

Figure 1 reveals the lack of research on the relationship between BIM and 3DCP, as there is no connection between them. This reflects the limited number of citations of these two concepts in the same document. Indeed, this literature review is characterized by a scarcity of articles that directly address the topic. It also demonstrates the lack of investigation into the interoperability between BIM and robotic arms. Thus, confirming the problematic of the parallel evolution between BIM and robotic 3DCP.

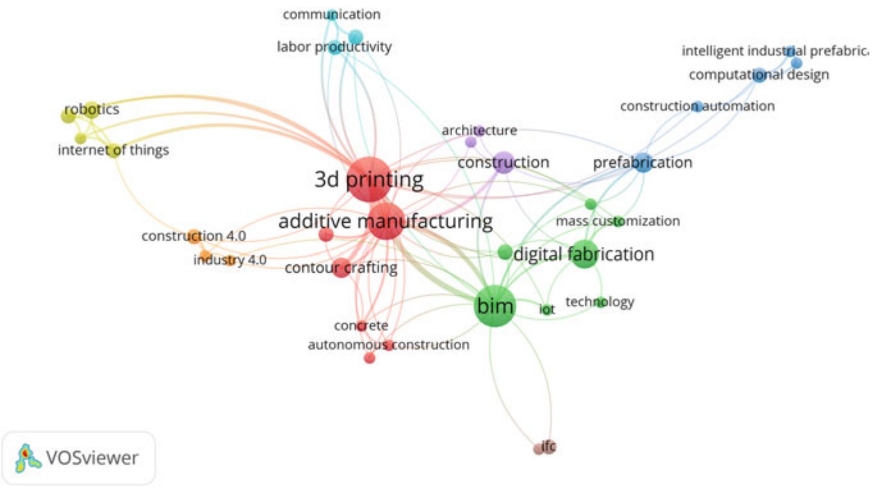

Fig. 1 Co-occurrence of authors' keywords in the literature review

3 Methodology

BIM and additive manufacturing represent two very broad domains that are evolving in parallel. It is not possible to summarize the totality of the processes used in BIM that could be applied to additive manufacturing. This is the case since the technological tools of the two fields are quite diverse. Therefore, only workflows involving 3D printing with a robotic arm are addressed. This method allows the realization of complex architecture and can be carried out with modeling tools allowing to control simultaneously the trajectory of the extruder and the model parameters [7]. This document focuses on concrete printing as the material used in this method is the most widely used in construction [1]. It identifies the various scenarios where BIM and 3DCP are used collectively and aims to develop a seamless integration between them.

To explore the issue of interoperability identified in the literature review, the state of its technological dimension between BIM and 3DCP with a robotic arm is defined. The approaches involving this association are then categorized according to the classification of [10] which addresses only the workflows characterizing parametric BIM modeling. Indeed, Janssen's methodology divides parametric BIM modeling between an embedded and coupled approach. The embedded approach is about using the software built-in functionalities. The coupled approach is subdivided to tightly coupled which associates two systems through the modeling software application programming interface (API), and loosely coupled, which involves a model exchange through the transfer of file formats. Adapting this methodology, our research categorizes the different approaches found in the literature review for using 3DCP in construction. It proposes two new approaches to apply BIM to this method. Finally, it suggests the most efficient approach by comparing the data transfers it involves and the functionalities it offers.

4 Technological Interoperability Between BIM and 3D Concrete Printing in Construction

Technological interoperability is the exchange of data and information in a digital environment. In construction, this aspect has been recognized as one of the significant barriers to the adoption of BIM in the industry due to the paradigm shift it brings [16]. Nevertheless, the use of BIM is currently expanding in the construction industry thanks to the potential of centralized information and facilitated collaboration. This level of adoption has not yet been reached in 3D concrete printing. The integration of BIM design activities into 3DCP offers the potential to significantly increase productivity by reducing implementation time and improving product quality. However, this integration still encounters critical challenges with respect to the transfer of information between BIM tools and automated construction systems. BIM is well known for its design of open file formats such as IFC. It is an open format that is in constant development and the reputation of this exchange technology is now well established since many of its aspects have reached maturity [4]. IFC is a file format based on objects rich in information to represent building data. Janssen et al. [11], 2 states that "the use of an open standardized file format ensures that the approach remains workflow agnostic." This has contributed to its growing popularity in the industry and most CAD systems include it in their export formats [5]. However, IFC is not the most common format for 3D printing as there are other well-known file formats such as OBJ, AMF or 3MF. Yet the most common import format used by 3D printers remains the STL or STEP format depending on the type of information to be transmitted [14]. This highlights the parallel evolution of BIM design and 3D concrete printing tools. This project is part of the effort to propose an optimized approach that will support technological interoperability in the adoption of 3DCP in construction.

5 Approaches for the Use of BIM for Robotic 3D Concrete Printing

5.1 Loosely Coupled Approach

According to Hager et al. [9], the workflow involving additive manufacturing begins with a model that is prepared in a 3D modeling application. It is then exported in a 3D data exchange format, often STL. This model is then sliced to constitute the successive deposited material layers. These layers define the control commands to position the extrusion head and start the printing of the model. This approach

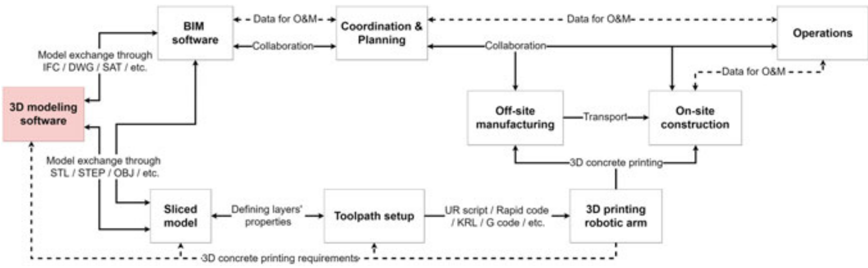

Fig. 2 Loosely coupled approach for applying robotic 3DCP in construction

is defined by Janssen [10] as loosely coupled because it involves an exchange of models between different software programs, typically a 3D modeling software and a digital fabrication software. However, the transfer of data throughout this process involves the risk of information loss. For example, the STL format only transmits geometric data and neglects information related to the component properties, such as the material properties or surface conditions. Moreover, the data processing in the slicing software is not always optimal [14]. As a result, a fragmented process occurs, losing critical information for the integration of the 3D printed project into a construction environment. This also concerns the BIM application's alternative to the workflow since the 3D model will be exported in a format accessible by BIM engines. Figure 2 is realized in order to explain the loosely coupled approach associating BIM. This workflow is considered the least efficient due to the amount of format conversion it requires and the number of modeling and fabrication tools that it involves. This demonstrates the importance of integrated processes as once the model export is done, all the parameters related to the model are lost. With this, the user ends up with a bare model that is hard to modify depending on the printing parameters. In fact, the printing process is not always optimal from the very first attempt, thus requiring modifications to the model according to the challenges encountered during the fabrication process. With such a method, all the steps related to 3D printing will have to be repeated from the beginning without any possibility of rewinding. This will not be efficient within the time constraints incurred during construction. Data for O&M and 3DCP requirements are illustrated in this figure and all subsequent figures as dotted lines since it is not the focus of this study, which is primarily aimed at the realization of the project.

In order to contribute to the evolution of robotic 3D concrete printing in construction, the integration of BIM in its development represent an appealing alternative. BIM has a lot of potential to offer from the perspective of its adaptability, the collaborative opportunity it offers and its ability to reduce costs [17]. Research has already been conducted to apply BIM to the loosely coupled type of approach [3, 19]. Yet most have not mentioned the parametric workflow and have been content with a simple export of the BIM model for printing. These studies have been focusing on the advantages of using BIM functionalities and neglecting the optimization of 3D printing. The benefit of this approach is illustrated in Fig. 3. Taking advantage of

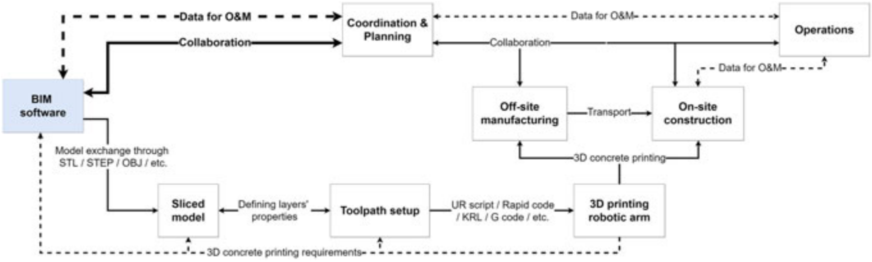

Fig. 3 Loosely coupled approach for applying robotic 3DCP in construction starting with a BIM software

BIM will lead to better integration in construction and allow better management of the 3D printed component throughout its lifecycle. It enables the use of BIM tools to predict clash detections and exploit the data collected for collaborative purposes.

In the context of this study, this process still presents a parallel evolution of BIM and robotic 3DCP. The use of a BIM software at the beginning of the process offers a considerable advantage. It allows a direct use of the information generated from the model and facilitates its integration into the construction environment. But this approach remains loosely coupled with 3D printing because it loses all the advantages of the embedded approach using BIM. By transmitting the model to the digital manufacturing tools, a discontinuity in the process is created, and a loss of information is possible.

5.2 *Moderately Coupled Approach*

In the context of this study, it was necessary to include another type of coupled approach other than those developed by Janssen [10]. The moderately coupled approach consists of adopting a tightly coupled approach on the one hand and a loosely coupled approach on the other. Examples of this approach can be identified through the use of parametric modeling tools such as Grasshopper. This methodology allows the application of visual programming for the control of the 3D printing robotic arm using rapid iterations. That enables the user to modify both geometry and toolpaths as well as machine parameters, and then simulate the results in a single environment [2]. It is a methodology that has been widely used in research projects such as the work of [13]. These tools will generate a script that will be transferred to the robotic arm to print the model and will be combined with a modeling software to produce a 3D printing simulation. This process is not only dependent on visual programming tools, as it can also be adopted with a modeling software integrating a programming and robotic simulation plugin.

According to the literature review, BIM integration has not been thoroughly investigated in this approach. This integration can be explained in other research that

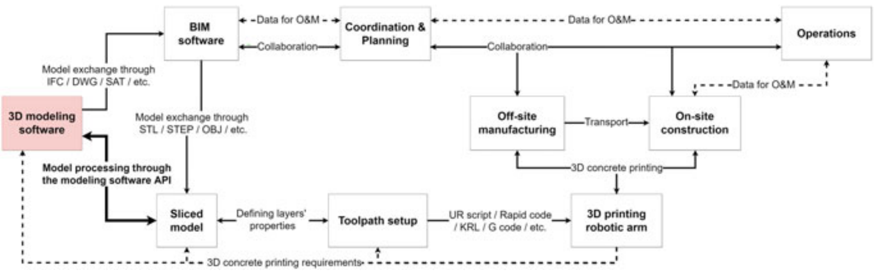

Fig. 4 Moderately coupled approach for applying robotic 3DCP in construction

addresses specifically parametric design. For example, the study by Janssen [10] discussed the possibility of transferring information using other plugins of visual programming like GeometryGym. But these tools only offer a means of exporting to IFC which implies a model exchange. Figure 4 illustrates that the process of applying BIM remains parallel to the 3D concrete printing process and is recognized as a moderately coupled approach. It involves model exchange on the one hand, and the use of parametric design tools using the modeling software API on the other.

5.3 *Proposed Tightly Coupled Approach*

This study presents two alternatives to improve the efficiency of the application of BIM to robotic 3D concrete printing. With the first alternative, it is possible to avoid the need for a model exchange format by using representational state transfer (REST) APIs. For example, this can be available with Speckle, which allows the transfer of 3D models between various design and analysis tools (Revit, Rhinoceros, Unity, Blender, etc.). Figure 5 illustrates this workflow which starts with a 3D modeling software like Rhinoceros. The model developed is then transferred to Revit (as a BIM software) in almost real time with Speckle. This workflow offers several opportunities for collaboration between the project participants and allows to collect a

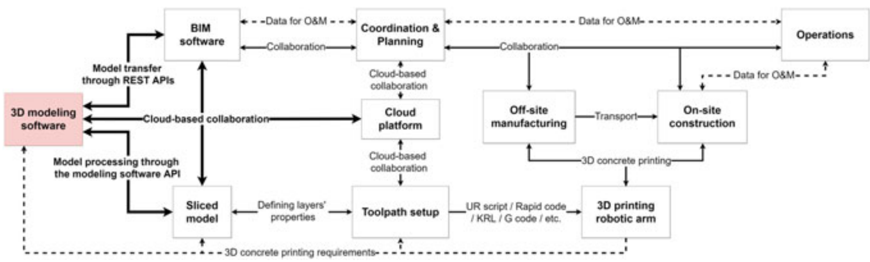

Fig. 5 Proposed tightly coupled approach for applying robotic 3DCP in construction starting with a 3D modeling software

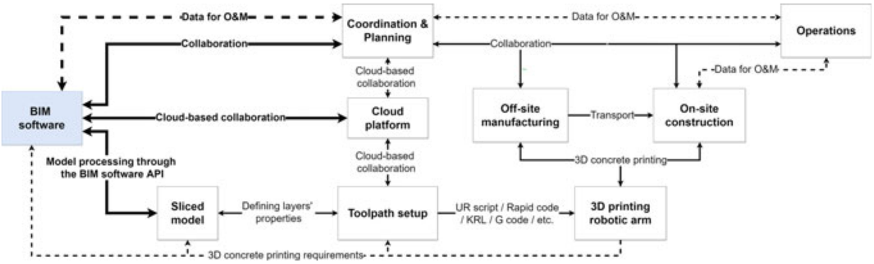

Fig. 6 Proposed tightly coupled approach for applying robotic 3DCP in construction starting with a BIM software

database of the 3D model evolution. In fact, it permits a parametric control of the 3D model and the printing mechanism in a simultaneous way. It allows the model to be transferred to a Web viewer enabling cloud-based collaboration and uses an object-based version control system to design and structure the data [15]. However, Speckle's performance is dependent on the volume of data to be transferred. It is not yet possible to transfer voluminous models instantly with Speckle, which raises the importance of data management.

To achieve a better adoption in construction and as demonstrated by the application of BIM to the loosely coupled approach. It is necessary to initiate the process with a BIM software for a smoother adoption in construction. In contrast to the moderately coupled approach, the second alternative illustrated in Fig. 6 proposes to start with a model developed with visual programming tools. This provides the advantage of having a tightly coupled BIM approach since these tools are directly linked to the BIM software API (Dynamo for its connection with Revit, Rhino.Inside.Revit for the Grasshopper/Revit combination or Live connection for the Grasshopper/Archicad combination, etc.). The quality and the number of plugins intended for digital fabrication vary between visual programming tools. For example, this approach is possible with Rhino.inside.Revit as it offers the necessary functionality to create 3D printing simulations. It allows to instantly generate printing scripts that can be transmitted to the robotic arm. This process offers design flexibility with centralized information, it reinforces the role of BIM as a facilitator of the adoption of robotic 3DCP. It provides both a model with the information required for its realization on the site or off-site, and also the simulation of its printing process.

Compared to the first alternative, the advantage of this workflow consists in its structured information since it starts with a BIM software. In addition, cloud-based collaboration is better supported by this process given the range of platforms available through the BIM processes. This approach presents the fewest steps in the information flow with no model exchange format. It limits the loss of information during model transitions and transforms transfer challenges through format conversion into transfer challenges through the API provided by the system used.

6 Suggested Approach

In this step, the suggested approach consists in the tightly coupled approach for applying robotic 3DCP in construction starting with a BIM software. Revit is taken as an example of BIM-modeling software and this approach is realized using the Rhino.Inside.Revit plugin. Therefore, the script for robotic printing is developed in Rhinoceros. Grasshopper is suggested since it is much more used in the digital fabrication environment compared to Dynamo. The case study focuses on the prefabrication of an observatory realized with robotic 3DCP. This observatory will be placed on the roof of a building inspired by the Morpheus hotel in Macau. The modeling process is developed in Grasshopper with the BIM schema provided by Rhino.Inside.Revit. The additive manufacturing script is also prepared in the same environment. As a result, the printing simulation and command lines are instantly generated. With Rhino.inside.Revit, it is Rhino running inside the Revit memory space. This means they can share all available data, saving considerable time and accuracy compared to loosely coupled approaches. No information transfer takes place through model exports and imports since the entire process is prepared in one environment. This combination will allow the use of all the advantages of both tools to have a multifunctional result. For example, the Speckle plugin can be used for collaboration between the various stakeholders of a project. It will be employed to transmit geometry information and exchange printing data in real time between the software it supports. It will allow the visualization of the model through a web viewer which will guarantee an efficient collaboration. Cloud-based collaboration can also be executed with Forge, BIM360 or Unity reflect for information management and collaboration. Fologram could be used for the augmented reality representation of the 3DCP simulation and the model used. Ladybug and Honeybee could also be used for the sustainable development aspect through the different analyses that these plugins offer. BIM tools can be used for clash detection when integrating into construction environments and all dimensions of BIM including project documentation. The result of this process is shown in Fig. 7, which illustrates the simultaneous visualization of the developed model and 3DCP simulation. This visualization is represented in four columns from left to right, in Rhinoceros, Revit, Speckle web viewer and in augmented reality through Fologram.

However, this approach has some limitations. 3D printing is based on meshes, and since Revit and Rhinoceros use different geometry engines, the use of Grasshopper models in Revit will not always result in perfect meshes. Moreover, meshes are often voluminous in data. Without reduction, they can cause limitations in their transfer to the cloud. This combination of tools gives a much more stable result in the management of boundary representations (Brep). In the case of 3D printing simulations, there are no good ways to embed an object animation in Revit as this software is not designed for this functionality. Nevertheless, these simulations can be supported in any other tightly coupled software such as Rhinoceros or Unity, which highlights the importance of information management. In spite of these limitations, the process remains more efficient than the loosely coupled approach. It keeps all the

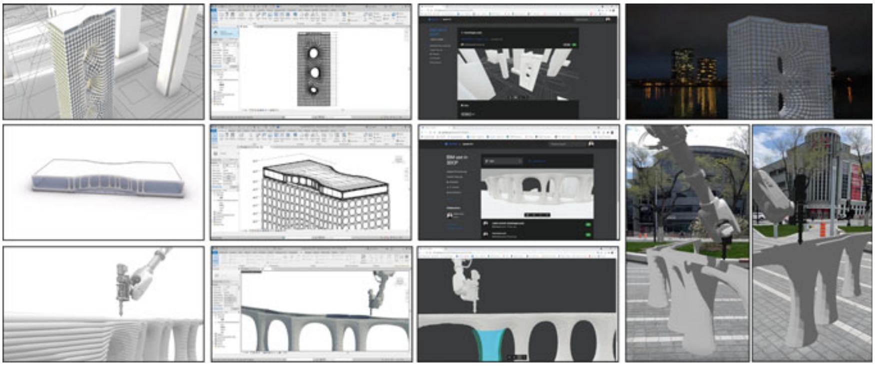

Fig. 7 Simultaneous visualization of the suggested process result in Rhinoceros, Revit, Speckle and Fologram

parameters of the design and printing process, and enables the modeling to be adjusted according to the printing tool. Rhino.Inside.Revit development defines a significant evolution of the technological interoperability between Revit and Rhinoceros. It offers a multitude of possible application tracks, such as the one addressed in this approach which is robotic 3D concrete printing.

7 Conclusion

BIM and robotic 3D concrete printing have evolved in parallel in the industry and this is due to the lack of interoperability between these two systems, among other reasons. This research focuses on the aspect of technological interoperability by comparing the different possible approaches for the application of BIM to robotic 3DCP. Based on the various scenarios evaluated, we suggest that the most efficient process consists in the tightly coupled approach starting with a BIM software. By using this approach, the need for exchange formats is avoided. The risk of information loss is reduced and technological interoperability between the two systems is improved. This study constitutes a step towards clarifying the advantage of integrating BIM into the workflow. Indeed, the application of BIM to robotic 3DCP is a very interesting alternative for off-site manufacturing and the standardization of printed objects. It improves collaboration between the various stakeholders of a construction project, especially on the MEP side. This will certainly influence the other dimensions of interoperability defined by Poirier et al. [16], i.e. the procedural, organizational and contextual dimensions of the two systems, which constitute future avenues for development.

The proposed methodology can apply not only to additive manufacturing, but also to the case of subtractive manufacturing or robotic manipulations. Fabrication of wood, for example, would constitute a quite promising development path since it requires both manufacturing and data. In this context, many other research directions can be explored, which reveals the potential of BIM's application to digital fabrication in construction.

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Enhanced CPM/LOB Repetitive Scheduling Formulation to Meet Deadlines

Tarek Hegazy and Kareem Mostafa

1 Introduction

Repetitive construction projects are projects where the same activities are repeated throughout a number of units (e.g., sections of a highway, floors of a tower, etc.). To best schedule this type of projects, construction crews are assigned so that each crew can move from one unit to another without interruptions, and the deadline is met. This helps the crews to maintain their work continuity, which saves the project time and cost [1, 3]. Therefore, using the Critical Path Method (CPM) alone to schedule repetitive projects is insufficient as it does not take into account resource and work continuity constraints [7, 13].

To address CPM shortcomings, researchers have developed multiple scheduling methods that cater to the particular needs of repetitive projects. Examples include Line Of Balance (LOB) [2], the Linear Scheduling Model [6], and the Repetitive Scheduling Method [5]. More recent developments include the works of [8–10, 12], and [4], and others.

Suhail and Neale [11] possibly represents the first approach to suggest a mathematical CPM/LOB formulation that integrates CPM network analysis and line-of-balance (LOB) method for repetitive scheduling to determine the task delivery rates and associated crews that meet a given deadline. Because projects can have multiple constraints, CPM/LOB formulation can work nicely for simple cases with identical units but violate deadlines under more practical situations, as discussed later, particularly if the calculated number of crews is not integer [14].

Despite the CPM/LOB benefits in determining the necessary crews that meet a given deadline, however, CPM/LOB formulation has several drawbacks that are addressed in this paper: (1) the formulation underestimates the number of crews,

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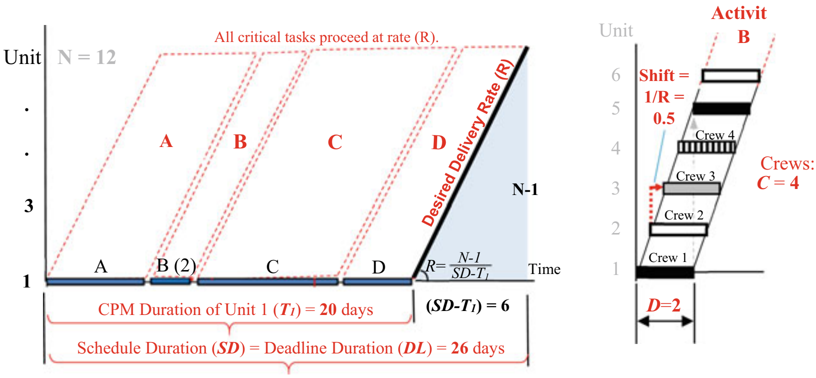
can lead to schedule gaps, and can result in a project delay although the deadline is relaxed; (2) it often results in non-integer start times for the crews, which is not practical; (3) it can violate deadlines in the practical case of projects with non-identical repetitive units; and (4) the schedule is not easy to draw and does not show the progress rate within each unit. In the remaining part of the paper, the standard CPM/LOB formulation is first presented, followed by the suggested solutions to the four CPM/LOB drawbacks, with examples demonstrating the improvements made to repetitive scheduling.

2 CPM/LOB Calculations

Given a certain deadline duration (DL) to complete N units, the CPM/LOB starts by performing CPM calculations to find the duration of one unit (T_i), as shown in Fig. 1. The deadline duration (DL) is considered as the schedule duration (SD) to be used for calculating the necessary crews. After completing the first unit of T_1 time, the triangle in Fig. 1a shows that the remaining $N-1$ units will be completed in the remaining time from the (i.e., SD$-T_1$), at the desired delivery rate (R) shown by the dark black line of the figure. As such, it is possible to force this rate on each activity (i), as calculated in Eq. 1. The adjustment TF$_i$ is the activity's total float that relaxes the desired rate for any non-critical task. With the desired rate calculated, the necessary number of crews C_i required to complete the project on time is then calculated using Eq. 2 which ensures the continuity of the crews work along the units. Finally, a revised rate is calculated based on the rounded crew number, in Eq. 3. Afterwards, the activity schedule can be drawn, as shown in Fig. 1b, by having each unit shifted an amount of time = $1/R$ from its previous unit.



(a) Calculation of desired rates based on project deadline (b) Enlarged schedule of task B

Fig. 1 CPM/LOB Analysis of the tasks' required shifted crews to meet deadline

$$\text{Task } i \text{ desired rate } (R_i) = \frac{N-1}{(\text{SD}--T_1+\text{TF}_i)} \tag{1}$$

$$\text{Task necessary crews } (C_i) = \text{Roundup}(D_i \times R_i) \tag{2}$$

$$\text{Task actual rate } (R_i) = C_i/D_i \tag{3}$$

Considering the small case in Fig. 1, with a deadline (DL) of 26 days, thus, schedule duration (SD) = 26 days. The single-unit CPM duration (T_1) is 20 days, and 12 repetitive units ($N = 12$). As such, using Eq. 1, the desired rate for activity B is equal to (12–1)/(26–20) = 1.83 units/day. Accordingly, the number of shifted crews to use in activity B (Eq. 2) becomes (C = Roundup ($D \times R = 2 \times 1.83$) = 4). With 4 crews, the actual rate of B becomes ($R = C/D = 2$ units/day, Eq. 3), and activity B can be drawn as shown in Fig. 1b, with each unit being shifted by ($1/R = 0.5$) days from the previous unit.

As an alternative to the shifted crew formulation in Fig. 1, which leads to non-integer crew start times, Hegazy [9] presented a modified formulation that determines the needed crews for the more practical case of using parallel crews. For the same 12-unit example of Figs. 1, 2a, show a parallel crew formulation. The desired delivery rate (R) for all tasks needs to be enforced on all critical tasks to meet the deadline. Considering task B, for example, its desired rate (dotted line) is parallel to the desired delivery line, with the crews arranged into S cycles of (C) crews to achieve this rate, and each cycle being a rectangular block. Looking at the two parallel triangles in Fig. 2a, it is possible to determine the necessary cycles (S) and crews (C) by equating the base distances (on the x-axis), i.e., $(S-1) \times D_B = (\text{SD} - T_1)$. Thus, the systematic formulation of the necessary parallel crews for any task i is as follows:

$$\text{Initial cycles } S_i \text{ of } C_i \text{ crews} = (\text{SD} - T_1)/D_i + 1 \tag{4}$$

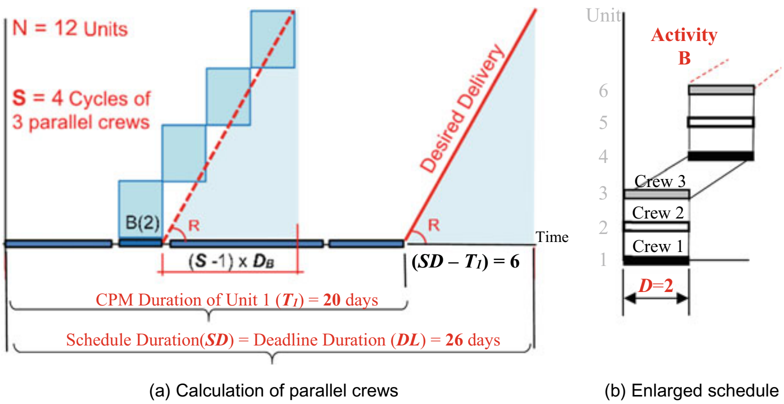


Fig. 2 CPM/LOB Analysis of the tasks' required parallel crews to meet deadline

$$\text{No. of Crews } C_i = \text{Roundup } (N/S_i);\ 1 \le C_i \le N \ \&\ C_i \le \text{Crew} - \text{Limit}_i \quad (5)$$

$$\text{Actual Cycles } S_i = \text{Roundup}(N/C_i) \quad (6)$$

Using Eqs. 4, 5 and 6 for task B in Fig. 2, the initial number of cycles (Eq. 4) is [(26 – 20)/2 + 1] = 4 cycles. Accordingly, the number of crews (C_B) = Roundup (12/4) = 3 (Eq. 5); and the actual cycles = Roundup (12/3) = 4. Thus, the final arrangement of this task is basically 3 crews engaged in 4 cycles to complete all units, as shown in the figure. As such, the 3 crews are first assigned to units 1, 2, and 3 in the first cycle, afterwards the crews will move to units 4, 5, and 6 in the second cycle (second rectangular block), then to units 7, 8, and 9 in the third cycle, etc., as shown in Fig. 2b.

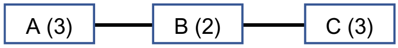
From the example in Figs. 1 and 2, the calculated number of crews for task B differ between the two calculation methods (4 shifted crews versus 3 parallel crews), yet crew work continuity is maintained in both arrangements. The final project duration, however, will be known only after drawing all the activities and considering any constraints. One advantage of the parallel formulation is that crew start times are integer values. In addition, it is possible to create a tightly-packed schedules by considering the crew-cycles of the activities as pieces of a Tetris game [8], so that all tasks have synchronized delivery rates that meet the deadline.

3 CPM/LOB Calculation Challenges

The example in Fig. 1 demonstrates the basic CPM/LOB calculations. To demonstrate its inherent challenges, consider the small project shown in Fig. 3, with a deadline of 20 days and 5 repetitive units. The standard CPM/LOB calculations are shown on the figure. Similar calculations for the parallel crew arrangement are in Fig. 4.

As seen in the schedule at the bottom of Figs. 3 and 4, Using CPM/LOB formulae resulted in a schedule that is 24 days long. This violates the original deadline of 20 days, as a result of the introduced time gaps in the schedule. It is noted that the first unit alone is completed in 12 days, as opposed to the original 8 days of the CPM duration.

The above example, as such, indicates the computational challenge that the CPM/LOB formulation suffers from. Using a relaxed deadline (case in Figs. 3 and 4) can result in a schedule that violates the relaxed deadline, as a result of the time gaps introduced into the schedule. This also shows that the computation, in general, underestimates the number of crews needed to meet deadlines.



Deadline (*DL*) = Schedule Duration (*SD*) = **20** days, CPM (T_1) = **8** days, Units (N) = **5**

	Duration *D*	Desired Rate, Eq.1, *R*	Necessary crews Eq. 2, ***C* = *D* x *R***	Actual Rate *R* = *C* / *D*	Shift *1/R*
A	3	4/(20-8) = 0.33	Roundup (3 x 0.33) = 1	1 / 3 = 0.33	3
B	2	4/(20-8) = 0.33	Roundup (2 x 0.33) = 1	1 / 2 = 0.50	2
C	3	4/(20-8) = 0.33	Roundup (3 x 0.33) = 1	1 / 3 = 0.33	3

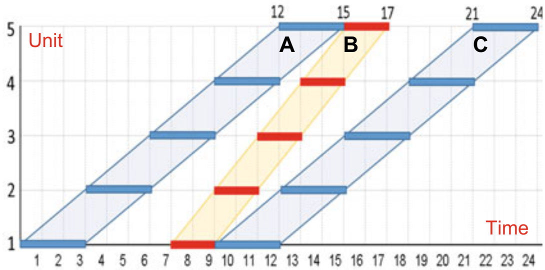
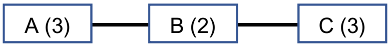


Fig. 3 CPM/LOB calculations for shifted crews exceed the deadline



Deadline (*DL*) = Schedule Duration (*SD*) = **20** days, CPM (T_1) = **8** days, Units (N) = **5**

	Duration *D*	No. of Cycles (*S*) Eq. 4	Necessary crews Eq. 5, **C = Roundup (*N/S*)**	Actual Cycles Eq. 6, **S = Roundup (*N/C*)**
A	3	(20-8)/3 + 1= 5	Roundup (5/5) = 1	5/1 = 5
B	2	(20-8)/2 + 1= 7	Roundup (5/7) = 1	5/1 = 5
C	3	(20-8)/3 + 1= 5	Roundup (5/5) = 1	5/1 = 5

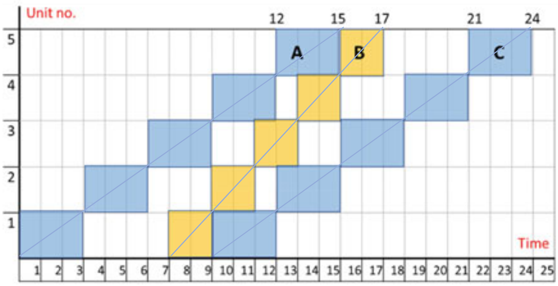


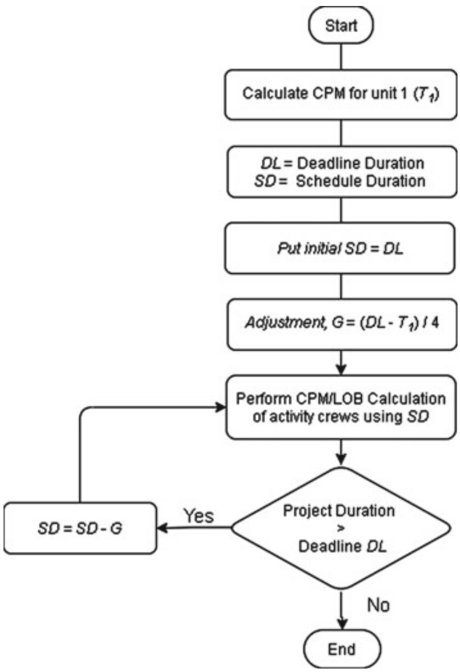
Fig. 4 CPM/LOB calculations for parallel crews exceed the deadline

4 Proposed Solutions

Computationally, the desired task rate determined using in Eq. 1 is the main parameter that controls the computation of needed crews, as a function of (SD − T_1) value, which is the difference between the schedule duration (initially equal to the deadline, i.e., SD = DL) and the CPM duration (T_1) for a single unit. As such, to reduce project duration and meet the deadline, there is a need to increase the delivery rate, and accordingly increase the crews to use. Therefore, increasing the delivery rate can easily be achieved by reducing the (SD − T_1) value, which in turn is achieved by reducing the schedule duration SD value used in the calculations (i.e., use SD *value that is less than* DL). Accordingly, it is possible to enhance CPM/LOB computation by introducing a simple loop that decreases the schedule duration (SD) value used in the calculations, step-by-step, and redo the calculations to meet the original deadline using the least number of crews. This improved CPM/LOB process is described in the flow chart of Fig. 5. To simplify the computation, the (SD − T_1) time is divided into only four intervals (four-step loop) of length *G*. In the first step, SD = DL, as presented earlier. Then, if the schedule produced in this step violates the DL duration, as shown in Figs. 3 and 4, the process continues to the next step in the loop and reduces the SD value by *G* days and re-performs the calculations. This loop terminates once a schedule is reached that satisfies the project DL deadline, to avoid using more resources than necessary to meet the deadline.

Along the revised computation, all crew start times are considered as integer values. Also, to facilitate practical consideration of non-identical units, the First-Come-First-Serve (FCFS) proposed by Hegazy [9] is adopted as an efficient approach to maintain crew work continuity yet reduce the time gaps in the schedule. Basically, the key concept in the crew assignment process is that it does not deal with the activity as a block with all crews together. Instead, it observes the continuity of each

Fig. 5 Flowchart of the improved CPM/LOB computation



crew individually. This leads to changing the geometry of the task arrangement to fit closely with its predecessor(s). It is also generic and applies to both identical and non-identical units, while respecting crew-work continuity and using integer crew start times. The FCFS crew assignment process is part of drawing the schedule and starts after the number of task crews has been computed using CPM/LOB equations. If, for example, a task is computed to need 4 crews, FCFS does not assign these crews to the first four units as traditionally done. Rather, it assigns the crews one by one, gives priority to waiting for a crew to finish before assigning it to succeeding unit, and in case all crews are busy, it checks if any additional crews are available to assign. First, it assigns crew 1 to unit 1 of the task, immediately after its predecessor. Afterwards, it checks if the same crew will be available before the next unit's predecessor is completed, it then assigns this crew to the next unit. For example, if three of the four task crews are assigned to units 1, 2, and 3, and if crew 2 is the earliest to complete its work and will become free when the predecessor of unit 4 is done, then it assigns crew 2 to unit 4, and so on. In general, FCFS proved to be efficient in reducing the time gaps of the schedule, and possibly reducing project duration.

5 Demonstration Example

In this section, two examples are given to demonstrate the efficiency of the developments made. First example continues on the schedule originally introduced in Fig. 3. Since the original deadline was 20 days and CPM duration was 8, the difference between the two values will be divided into four segments of equal length ($G = (20 - 8)/4 = 3$ days). As shown before in Fig. 2, when the value of SD was set to 20 days (the original deadline), the resulting CPM/LOB schedule ended up as 24 days. This is unacceptable as it is beyond the project deadline. Hence, the introduced computation loop used in its first cycle a smaller SD value (revised SD $= 20 - 3=17$). The calculations and the resulting schedules using this deadline can be seen in Fig. 6a and b, for shifted and parallel crews, respectively. Since the durations of the improved schedules are less than the project original deadline of 20 days, the process terminates after one cycle of the loop. If that was not the case, a new SD value of 14 days ($17 - 3$) would have been proposed and a new schedule would have been developed using the revised deadline. The parallel-crews schedule of Fig. 6b maintains crew continuity while putting all crews with integer start times.

Example 1: The second example demonstrates the more practical aspects of repetitive scheduling that have variety of constraints such as non-identical tasks and specific sequence for the units. This hypothetical example is a small pipeline installation project with 10 sections, all sections are 20 feet long, except sections 5 and 6, which are 10 feet and 30 feet, respectively. The task durations are shown on Fig. 7, with the durations of sections 5 and 6 need to be adjusted, proportional to their relative sizes. The project involves constructing the 10 sections in 24 days. To save project time, it is decided that Activity A must use 2 crews from each side of the pipeline (total 4

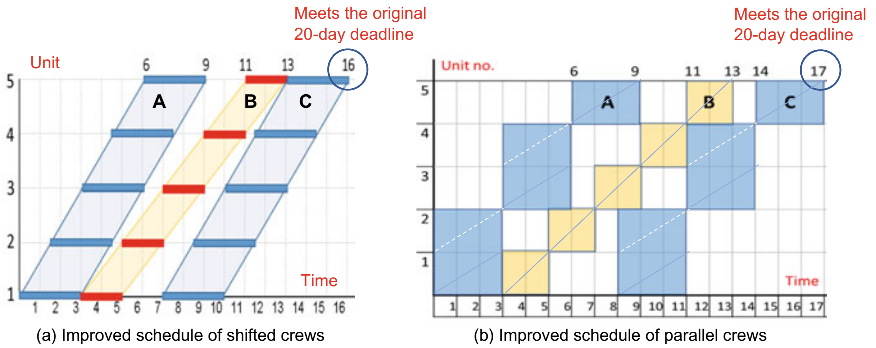


Fig. 6 Schedules developed using the proposed computation meet the original deadline

Deadline (*DL*) = **24** days, CPM (T_1) = **12** days, Units (N) = **10**.
Note: In sections 5 and 6, task durations are multiplied by 0.5 and 1.5, respectively.

	Duration *D*	Desired Rate, Eq.1, ***R***	Necessary crews Eq. 2, ***C = D x R***
A	3	9/(24-12) = 0.75	Roundup (3 x 0.75) = 3, Use 4
B	2	9/(24-12) = 0.75	Roundup (2 x 0.75) = 2
C	3	9/(24-12) = 0.75	Roundup (3 x 0.75) = 3
D	4	9/(24-12) = 0.75	Roundup (4 x 0.75) = 3

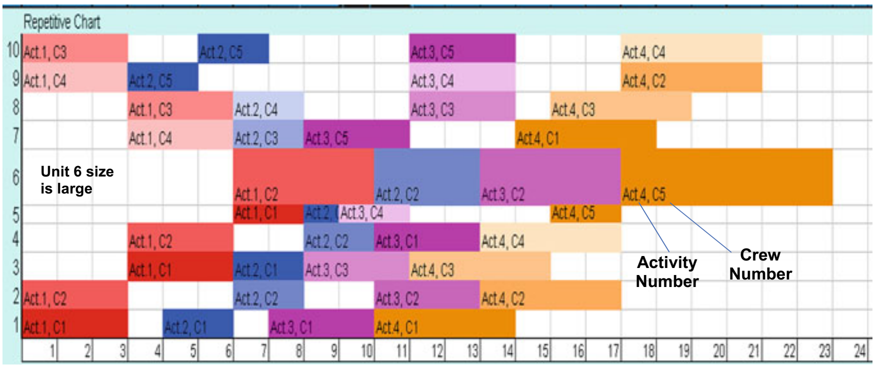


Fig. 7 Schedule for example 2 meets the 24-day deadline

crews), thus, two crews go from sections 10 to 9 to 8 to 7 to 6, while the other two crews go from 1 to 2 to 3 to 4 to 5.

The repetitive schedule at the bottom of Fig. 7 shows the result of applying the proposed CPM/LOB improvements. On the vertical axis, it shows the relative sizes of units 5 and 6, as compared to the all the standard ones. Units 5 and 6 durations were adjusted and rounded up to nearest integers. All conditions are met and crew start times are integer. For clarity, each task is marked by the activity number and the crew number. The schedule also has minimum gaps, meets the deadline, and maintains the continuity of work for all crews. The number of crews in the schedule are more than the calculated values in the table of Fig. 7, indicating that the proposed calculation loop was applied to obtain the necessary number of crews to meet the deadline. In the schedule, the number of crews used in the activities are: 4, 5, 5, 5, respectively.

6 Summary and Conclusion

The paper presented a general formulation to create realistic and legible repetitive schedules that do not suffer from the drawbacks of the traditional CPM/LOB formulation. The proposed formulation introduces a loop of checking deadline violation and adjusting the calculation, until the deadline is met. This formulation calculates the necessary crews and the necessary adjustments using only one parameter which is the project deadline, which is easier to manage as opposed to attempting to tweak each activity manually. This formulation also allows schedulers to meet project deadlines, considering variety of practical constraints such as non-identical tasks, without resorting to more expensive construction methods to crash the activities. To further tighten the schedule and avoid time gaps, the first-come-first-served (FCFS) crew assignment strategy has been adopted along with improved schedule visuals to legibly show the schedule and crew assignments to all stakeholders. The presented examples show the flexibility of the improved CPM/LOB formulation to meet deadlines of complex repetitive schedules. Future research includes examining the applicability of the proposed algorithm on real-world megaprojects both in terms of practicality and abiding by the project's requirements and constraints, as well as the algorithm's computational requirements.

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A Risk Management Tool for Construction Sector India During Covid-19 Crisis

S. Jha, M. Bhoi, and U. Chaduvula

1 Introduction

In construction industry, main focus was considered on project management that involves time and cost management. Delays in schedule of the project, cost overruns are caused due to some uncertainties that occur during or before the execution of activity. Thus, it is very important that such uncertainty should be taken care of and should be eliminated at the dedicated stage of the project. Now-a-days, risk management has become very necessary in construction project to avoid any delays or losses of resources and many methods have been developed to perform risk analysis for the project which involves risk identification, risk analysis, risk mitigation. Risks in the project can be eliminated, transfer or reduced to avoid any loss in the project and assist to prepare a contingency plan. Recently, an uncertain situation happened in India for which no construction firms or organizations were prepared i.e., COVID-19. COVID-19 crisis hit the construction sector very severely as suddenly the construction stopped for a long time, there was no cash-flow, no execution of work that lead to a great loss for the project stakeholders and other participants. In such situation, risk management was very essential to avoid further losses using an efficient and effective analysis approach. Many methods have been developed to carry out risk analysis which can be explored through literature survey in further section. During this crisis, an immediate risk analysis for the construction project is necessary to cope up the losses occurred and to get the schedule on track to avoid further delays. Through literature survey, Expected Value Method (EVM) has been considered for this study as it is more convenient approach and easy to follow method compared with other developed methods. Since, it was an unexpected event it is necessary to have a comprehensive picture of the construction work and immediate mitigation actions to cover all the gaps suffered due to pandemic. Thus, this study contributes to

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identify the potential risk factors that affected the construction works during COVID-19 and carry out a survey to get experts' opinions about the impact of the risk factors as well as inclusion of other risk factors according to their experience. Using EVM technique, severity of each risk can be concluded in a simple way without any complicated calculations and it is easy to follow providing satisfactory results which can be useful to make decision making process faster. EVM doesn't require any cost resources to implement just the experts' opinions which is why it is more convenient and efficient to recognize the potential risks and average severity outcomes.

2 Literature Review

Jia et al. [1] aimed at developing a contemporary applied solution for project managers to know the effective risk management approach by Risk management (RM) maturity evaluation. They have developed a blueprint of the RM maturity system for complex projects which will provide the efficient and effective evaluation of the RM approach for critical risk factors using Analytical Network Process (ANP). The model has been illustrated using a case study which seems to show satisfactory results. Gładysz et al. [2] proposed a PERT-aimed model for risk management which differentiates various potential risk categories of project and assist in evaluating which risks can be eliminated in order to reduce cost with estimated completion time. The uniqueness of the model is that it provides a minimal risk elimination approach to satisfy the completion cost and time. Salawu and Abdullah [3] aimed at assessing the risk management potentiality of the construction firms involved in highway reconstruction projects in Nigeria. They have developed a framework based on four-level fuzzy sets which will assess and measure the risk management maturity of construction firms with respect to the contractors and assist in knowing their weakness and strength which will lead to better selection of highway projects and contractors' risk response planning.

Qazi et al. [4] covered the research gap of project failures due to risk difficulty by proposing a new approach to develop a relationship between project difficulty and project risk dependence. The approach includes relationship between project difficulty, potential risks due to difficulty and project goals. They identified the potential risks and selected effective risk reduction techniques keeping in mind the relationship of project difficulty and risks and project goals. They have defined the approach through a replica study. Szymanski [5] did a detailed study on risk management approaches in construction projects by defining how a risk identification process should be done. The study showed identification of risks which leads to analysing those risks through qualitative and quantitative methods defining categories as to which risks can be eliminated, dispersed or absorbed. The study also showed various methods which can be used to reduce or eliminate the potential risks from the construction projects.

Keshk et al. [6] did a detailed study on risk management strategies and defined various qualitative and quantitative methods for risk reduction or mitigation. For qualitative analysis, they have proposed risk rating matrix which shows the probability of the each risk in the project. For quantitative analysis, they have proposed decision tree method, Simulation method i.e., Monte-Carlo Simulation, thus by defining these approaches they have showed effective risk management techniques and assist in preparing contingency plan. Sarkar et al. [7] aimed at comparing the risk analysis methods i.e., Fuzzy Analytical Hierarchy process (FAHP), Fuzzy Expected Value Method (FEVM) and Modified Expected Value Method (MEVM) for an elevated metro rail corridor project for major activities. The results showed that Fuzzy Expected Value Method is more accurate than other methods, FAHP and MEVM gives accurate results for limited major activities. Filippetto et al. [8] proposed a computer-based framework to reduce the potential risks in the project by predicting the risks at each stage of the project. They have developed a model called Atropos which recommends the risks to the ongoing projects using the data of the executed projects and Bots in Atropos suggests new recommendations at the same time. The results showed 73% acceptability and 83% effectiveness in the recommendation from previous executed projects. This model is quite an effective tool to identify the risks in ongoing projects using similarities and characteristics of executed projects.

This study aims at using Expected Value Method (EVM) to identify the potential risks due to COVID-19 in construction sector and analyse them to prepare a contingency plan to avoid further losses in the project. A 6-lane highway project has been considered for the analysis. EVM considered to be an effective tool for the risk analysis which gives satisfactory results and assist the project members to build an effective risk response plan. Further sections shows the analysis and results of the risk management approach techniques.

3 Research Methodology

Risk management is an important factor in the construction sector to achieve the project goals in an effective and efficient manner. Many methods has been developed to perform risk analysis for the construction project like Expected Value Method (EVM), Analytical Hierarchy Process (AHP), Fuzzy Analytical Hierarchy Process (FAHP) etc. From all these methods, Expected Value Method (EVM) is quite a satisfactory method to perform risk analysis as it is easy to follow involving just experts' opinions to foresight the risks for the project in order to prepare a contingency plan to avoid delays, loss of resources etc. In this study, risk analysis has been carried out by using expected value method for a construction sector. First of all, possible risks were identified which may occur in construction sector due to COVID-19 crisis which were shown in the Table 1. The possible risks identified were classified in four categories i.e., completion risk, commercial risk, contractual risk and health and safety risk. These categories have been considered through general survey and experts' opinion where completion risks involves the risks variables that affects the

Table 1 Sample response sheet

Questionnaire for major activity risks due to COVID-19					
Name of respondent					*Organization*
Designation					*Experience*
Risk analysis by expected value method					
Sr. No.	*Risk description*		*Likelihood* (0–1)	*Weightage* (ΣW = 1)	*Impact* (0–1)
Completion risk					
1	Rescheduling of activities				
2	Unavailability of labourers				
3	Unavailability of materials				
4	Unavailability of equipments				
5	Supply chain disruptions				
6	Cash flow concerns				
7	Financing restrictions				
8	Alternative methods selection to comply work as per government instructions				
Commercial risk					
9	Commodity price swings				
10	Labour-cost escalations				
11	Higher costs of materials				
12	Limited pool of resources due to travel restrictions				
13	Extension of project completion dates				
14	Increased financing, management and developer costs				
Contractual risk					
15	Negotiation in contract				

(continued)

Table 1 (continued)

Questionnaire for major activity risks due to COVID-19					
Name of respondent					*Organization*
Designation					*Experience*
Risk analysis by expected value method					
Sr. No.	*Risk description*		*Likelihood* (0–1)	*Weightage* ($\Sigma W = 1$)	*Impact* (0–1)
16	Distribution adjustment for shares				
17	Recovery of performance costs				
18	Compensation to contractors				
Health and safety risk					
19	Safety of all project team members				
20	Lack of Social distancing				
21	Unavailability of PPE (Personnel Protective Equipments)				
22	Lack of measuring health instruments				

completion schedule of the project for e.g., financing restrictions is dedicated to completion risk category as cost resources are required to avail facilities to complete the task and due to losses suffered by stakeholders and other participants, financial resources have been limited. Similarly, Commercial risk category involves the risk variables that represents the economic and productive profile of the construction project. Contractual risk category involves the risk variables that represents the contracts agreement and shares involvement. Health and safety risk category involves the risk variables that represents the safety of the whole team and site according to the government norms due to pandemic.

After identifying the risks and putting them in the respective categories, risk analysis has been carried using Expected value method (EVM) for statistical analysis. Expected value method enables the knowledge of future events which may or may not occur. It helps in identifying the possible risks and their severity to the project in order to develop a contingency plan to maintain the project on track and schedule to avoid any loss of resources or delays. For the analysis using EVM, a response sheet including all the risks has been prepared which involves categories i.e., Likelihood, Weightage and Impact.

Likelihood—defines the probability of an risk or uncertainty to occur.

Impact—defines the effectiveness of the risk or uncertainty on particular activity.

Weightage—defines the weightage of whole risk to the project which sum equal to 1.

The response sheet has been shown in Table 1.

In response sheet, likelihood factor was designated a scale of 0–1, thus for each risk likelihood factor will be scaled in between 0–1. Similarly, impact factor was designated a scale of 0.-1, thus for each risk impact factor will be scaled in between 0–1 and weightage of the risk should be scaled between 0–1 but the weightage for whole category should be equals to 1 i.e., $\sum W = 1$. The response sheet was passed on to various experts and practitioners from different organizations working under same field and projects. In total 30 responses were collected, analysed and a final response sheet was prepared which is shown in Table 2.

The following Fig. 1 shows the respective respondents considered in this study to have their experienced approach in providing their opinions to assist in analysing the severity of the impact due to pandemic.

Thus, from all 30 responses from experts and practitioners a final response sheet with likelihood, weightage and impact for all the risks was prepared.

Final response sheet has been normalized by taking the average of all 30 responses for each risk which can be shown below with the following approach. This approach has been followed for likelihood, weightage and impact of all risks.

Risk = Average (Sum of all 30 responses for that particular risk).

Further, Composite Likelihood Factor (CLF) and Composite Impact Factor (CIF) was evaluated on the basis of the responses collected for each risk. CLF and CIF can be calculated as shown:

$$\text{Composite Likelihood Factor(CLF)} = \text{Likelihood}(L_i) \times \text{Weightage}(W_i) \tag{1}$$

$$\text{Composite Impact Factor(CIF)} = \text{Impact}(I) \times \text{Weightage}(W_i) \tag{2}$$

Further, Risk Severity has been evaluated to know how severe the risks will be on the project. Thus, Risk Severity can be calculated as shown:

$$\text{Risk Severity} = \text{Composite Likelihood Factor(CLF)} \times \text{Composite Impact Factor(CIF)} \tag{3}$$

Risk severity enables the knowledge of how severe a risk will be for the project and how to deal with it according to its priority. Risk analysis helps the project team members to know which risks affects the project more and which risks can be neglected. Thus, a contingency plan can be prepared accordingly to avoid loss in the project and achieve the objectives as per stakeholder's perspective.

Table 2 Final response sheet for risk analysis

Questionnaire for major activity risks due to COVID-19					
	Name of Respondent				Organization
	Designation				Experience
RISK ANALYSIS BY EXPECTED VALUE METHOD					
Sr. No.	Risk description		Likelihood (0–1)	Weightage (ΣW = 1)	Impact (0–1)
Completion risk					
1	Rescheduling of activities		0.65	0.22	0.6
2	Unavailability of labourers		0.6	0.10	0.5
3	Unavailability of materials		0.4	0.12	0.6
4	Unavailability of equipments		0.4	0.11	0.6
5	Supply chain disruptions		0.5	0.10	0.55
6	Cash flow concerns		0.6	0.13	0.7
7	Financing restrictions		0.6	0.13	0.6
8	Alternative methods selection to comply work as per government instructions		0.6	0.09	0.66
Commercial risk					
9	Commodity price swings		0.5	0.3	0.6
10	Labour-cost escalations		0.6	0.11	0.6
11	Higher costs of materials		0.6	0.13	0.5
12	Limited pool of resources due to travel restrictions		0.6	0.14	0.6
13	Extension of project completion dates		0.7	0.13	0.6
14	Increased financing, management and developer costs		0.6	0.2	0.7
Contractual risk					
15	Negotiation in contract		0.6	0.3	0.5

(continued)

Table 2 (continued)

Questionnaire for major activity risks due to COVID-19					
	Name of Respondent				Organization
	Designation				Experience
RISK ANALYSIS BY EXPECTED VALUE METHOD					
Sr. No.	Risk description		Likelihood (0–1)	Weightage ($\Sigma W = 1$)	Impact (0–1)
16	Distribution adjustment for shares		0.5	0.25	0.5
17	Recovery of performance costs		0.6	0.22	0.6
18	Compensation to contractors		0.6	0.2	0.6
Health and safety risk					
19	Safety of all project team members		0.7	0.3	0.7
20	Lack of Social distancing		0.7	0.22	0.6
21	Unavailability of PPE (Personnel Protective Equipments)		0.6	0.2	0.6
22	Lack of measuring health instruments		0.5	0.25	0.7

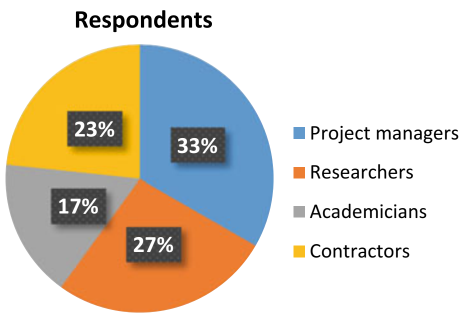

Fig. 1 Types of respondents

4 Analysis and Results

This study aims at identifying the possible risks in the construction projects due to COVID-19 crisis and analyse the severity of the risks using Expected Value Method (EVM) which will assist the project members to prepare a contingency plan to bring the project schedule on track and avoid any further delays and losses of resources. As discussed in previous section, possible risks were identified and a response sheet was prepared which was passed on to various experts and practitioners to provide their valuable responses. A final response sheet was prepared form all 30 responses collected and further calculation involving Composite likelihood factor (CLF), Composite impact factor (CIF) and Risk severity was evaluated which has been shown in the Table 3.

As mentioned in Table 3, risk severity has been calculated using equation [3], also qualitative risk severity has also been evaluated based on the linguistic term defined for the particular range which has been shown in Table 4. These linguistic term for particular range has been defined based on the risk severity results.

As mentioned in Table 4, qualitative risk severity has been designated according to the quantitative risk severity. Further, ranking has been done as shown in Table 4 which indicates the priority of the risk to be dealt with. Figure 2 shows the risk severity of each risk and its priority.

From Fig. 2, it can be clearly observed that 19th risk i.e., safety of all project team members has high risk severity and it becomes the first priority to deal with so that project progress cannot get hindered and can be completed without any further losses. Similarly, 15th risk i.e., negotiation in the contract is second most severe risk which may affect the project hence, it can dealt with on second priority. These graphical representation will provide the best view to know the risk severity so that the project members can plan accordingly to deal with the risks to avoid further losses in the project.

From Fig. 3, it can be observed that health and safety risk are at severe risk and should be on first priority and similarly, contractual risk will be on second priority. Health and safety risk is severe because of the pandemic situation COVID-19 safety is the first priority which can be clearly seen from the analysis. Contractual risk comes second because contracts are signed before the project starts and since the situation was unexpected shut down of the project or delay in the schedule of the project happened which basically leads to re-structuring the contract which involves many stakeholders, contracts and each with different views. Overall, Expected Vale Method (EVM) provides a detailed profile of the risk and its severity and assist in developing the contingency plan for the project.

5 Conclusion

Uncertainty is a major problem in construction sector and in such pandemic situation, construction sector was hit severely due to COVID-19 which was unexpected and thus, risk management becomes very important for the construction projects as a great loss was faced due COVID-19 crisis. In order to identify the risks due to COVID-19 and know the risk severity, this paper aimed at identifying the possible risks and analyse those risks using Expected Value Method (EVM) which will provide the risk severity of each risk and its priority to deal with and thus, assist the project members to prepare contingency plan accordingly to avoid any further losses of resources in the project. The following conclusions were made:

Table 3 Risk analysis by expected value method

	Questionnaire for major activity risks due to COVID-19									
	Name of Respondent					Organization				
	Designation					Experience				
RISK ANALYSIS BY EXPECTED VALUE METHOD										
Sr.No	Risk Description		Likelihood (0–1)	Weightage (ΣW = 1)	Impact (0–1)	CLF = (Li*Wi)	CIF = (Ii*Wi)	Risk Severity = (CLF*CIF)	Qualitative Risk severity	Ranking
Completion risk										
1	Rescheduling of activities		0.65	0.22	0.6	0.140	0.123	0.017	Low risk	**6**
2	Unavailability of labourers		0.6	0.10	0.5	0.062	0.054	0.003	Very low risk	**20**
3	Unavailability of materials		0.4	0.12	0.6	0.046	0.064	0.003	Very low risk	**21**
4	Unavailability of equipments		0.4	0.11	0.6	0.051	0.067	0.003	Very low risk	**22**
5	Supply chain disruptions		0.5	0.10	0.55	0.053	0.057	0.003	Very low risk	**19**
6	Cash flow concerns		0.6	0.13	0.7	0.081	0.097	0.008	Very low risk	**12**
7	Financing restrictions		0.6	0.13	0.6	0.083	0.075	0.006	Very low risk	**15**
8	Alternative methods selection to comply work as per government instructions		0.6	0.09	0.66	0.061	0.062	0.004	Very low risk	**18**

(continued)

Table 3 (continued)

	Questionnaire for major activity risks due to COVID-19									
	Name of Respondent					Organization				
	Designation					Experience				
RISK ANALYSIS BY EXPECTED VALUE METHOD										
Sr.No	Risk Description		Likelihood (0–1)	Weightage (ΣW = 1)	Impact (0–1)	CLF = (Li*Wi)	CIF = (Ii*Wi)	Risk Severity = (CLF*CIF)	Qualitative Risk severity	Ranking
Commercial risk										
9	Commodity price swings		0.5	0.3	0.6	0.152	0.162	0.025	Medium risk	**3**
10	Labour-cost escalations		0.6	0.11	0.6	0.071	0.069	0.005	Very low risk	**16**
11	Higher costs of materials		0.6	0.13	0.5	0.080	0.062	0.005	Very low risk	**17**
12	Limited pool of resources due to travel restrictions		0.6	0.14	0.6	0.082	0.079	0.007	Very low risk	**14**
13	Extension of project completion dates		0.7	0.13	0.6	0.087	0.083	0.007	Very low risk	**13**

(continued)

Table 3 (continued)

	Questionnaire for major activity risks due to COVID-19									
	Name of Respondent					Organization				
	Designation					Experience				
RISK ANALYSIS BY EXPECTED VALUE METHOD										
Sr.No	Risk Description		Likelihood (0–1)	Weightage (ΣW = 1)	Impact (0–1)	CLF = (Li*Wi)	CIF = (Ii*Wi)	Risk Severity = (CLF*CIF)	Qualitative Risk severity	Ranking
14	Increased financing, management and developer costs		0.6	0.2	0.7	0.112	0.120	0.013	Low risk	**10**
Contractual risk										
15	Negotiation in contract		0.6	0.3	0.5	0.190	0.144	0.027	Medium risk	**2**
16	Distribution adjustment for shares		0.5	0.25	0.5	0.134	0.125	0.017	Low risk	**7**
17	Recovery of performance costs		0.6	0.22	0.6	0.126	0.120	0.015	Low risk	**8**

(continued)

Table 3 (continued)

	Questionnaire for major activity risks due to COVID-19									
	Name of Respondent					Organization				
	Designation					Experience				
RISK ANALYSIS BY EXPECTED VALUE METHOD										
Sr.No	Risk Description		Likelihood (0–1)	Weightage ($\Sigma W = 1$)	Impact (0–1)	CLF = (Li*Wi)	CIF = (Ii*Wi)	Risk Severity = (CLF*CIF)	Qualitative Risk severity	Ranking
18	Compensation to contractors		0.6	0.2	0.6	0.110	0.120	0.013	Low risk	**11**
Health and safety risk										
19	Safety of all project team members		0.7	0.3	0.7	0.186	0.182	0.034	High risk	**1**
20	Lack of Social distancing		0.7	0.22	0.6	0.147	0.139	0.020	Low risk	**5**
21	Unavailability of PPE (Personnel Protective Equipments)		0.6	0.2	0.6	0.122	0.119	0.014	Low risk	**9**
22	Lack of measuring health instruments		0.5	0.25	0.7	0.125	0.173	0.022	Medium risk	**4**

Table 4 Risk severity and its linguistic terms

Risk severity	Linguistic term
0.000–0.01	Very low risk
0.011–0.02	Low risk
0.021–0.03	Medium risk
0.031–0.04	High risk
0.041–0.05	Very high risk

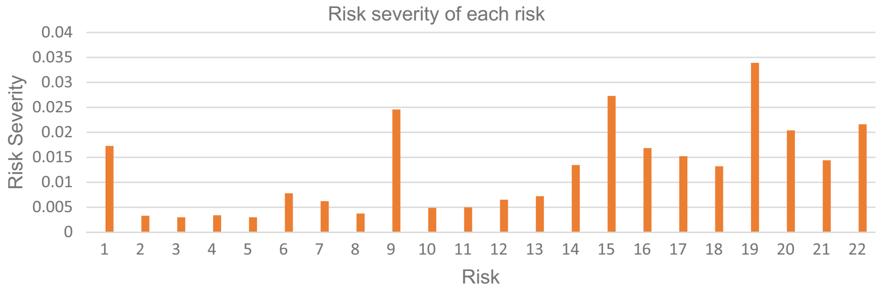

Fig. 2 Risk severity of each risk

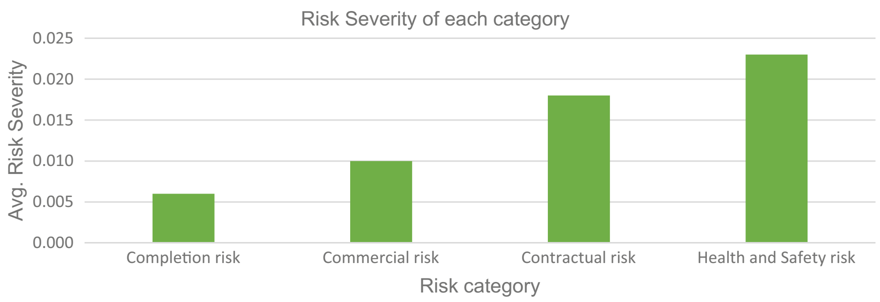

Fig. 3 Risk severity of each category

- Expected Value Method (EVM) was considered to analyse the risks as it is convenient method and easy to follow. It does not involve any complex structure and provides detailed and satisfactory results which will assist in preparing a contingency plan for the risk management.
- The results from Expected Value Method showed the risk severity of each risks which indicates Health and Safety risk to be at high level, Contractual risk at medium level and Completion risk & Commercial risk at low level.
- Expected Value Method (EVM) is an effective and efficient tool for risk management and provided the satisfactory results to manage risks in order to avoid any further losses in construction sector due to COVID-19 crisis.

6 Limitations

This study is limited to general risk variables involvement for every construction project that may be occurred due to COVID-19 crisis.

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Situation Awareness Based Smart Contract for Modular Construction

Huaming Li, Gongfan Chen, Min Liu, Simon M. Hsiang, and Ashtad Jarvamardi

1 Introduction

To achieve high productivity, construction site managers have to constantly face three challenges: tracking project progress, coordinating task handoffs under frequent interruptions, and motivating reliable work plan commitment of specialty trades. It is a common practice to devote a significant amount of management time and effort to check production progress. This task is usually undertaken by multiple project engineers. Because this is done in the ever-changing environment on job sites, it is both time-consuming and difficult to obtain accurate records. The second challenge is to manage interruptions of the work plan in the middle of the execution. The interruption can come from genenal contractors (GCs), suppliers, or subcontractors due to change order, delayed material delivery, or delayed completion of prerequisite work. When this happens, specialty trades have to stop in the middle of their work and adjust their plan on the spot with short or no notice, which can significantly cause their productivity loss. The third challenge is to motivate reliable

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work plan commitment of specialty trades. In the current construction practice, the penalty of delayed completion is usually not enforced until project completion or near completion. Project managers need to have a tool to help them to track the progress and motivate reliabile delivery timely, transparently, and objectively. Such a need is especially critical for modular construction project under the impact of COVID pandemic because of delay caused by the uncertainty and disruption of manuracturing and shipping time in supply chain.

Therefore, managers need a mechanism to motivate reliable work plan commitment for specialty trades promptly. This research selected a high-rise residential project using Prefabricated Bathroom Unit (PBUs) modules as a case study to develop a Blockchain platform. The objectives of this research are to (1) investigate the PBU delivery reliability impact on on-site installation productivity, and (2) establish a situation awareness Smart Contract to motivate reliable prefabricated construction material delivery. PBU delivery and installation data were collected from a high-rise residential project in Singapore. A STROBCOPE-based computer simulation model was established to study the productivity performance under different delivery scenarios. Smart contracts and a Blockchain platform were built to facilitate and motivate reliable delivery. The findings will be helpful for construction managers to better utilize the benefits of modular construction facing the challenge of uncertainty in the supply chain and shortage of skilled workers and working space.

2 Literature Review

2.1 Simulation for the Dynamics Between Delivery and On-Site Installation

Simulation method was used as an effective approach to better understand complex interactions and uncertainties in construction operations [1]. Simulation can investigate the characteristics of variability [2] and optimum trade-off [7] to evaluate the effectiveness of a control policy and deal with unexpected variability prior to its implementation in a real project [9]. Bamana et al. [4], Goh and Goh [6] constructed a simulation model to assess the impacts of projects with or without just-in-time (JIT) deliveries. Their results revealed a reduction in cycle time and improvements in labor productivity when implementing the JIT. Liu et al. [13] used discrete event simulation to evaluate the different supply chain configurations and the impacts on the overall project, and the results indicated the importance of supply chain configurations and multi-supplier boosts the manufacturing efficiency and consistency. The work of Jung et al. [10] revealed that construction and material supply processes should be viewed as one system and on-site storage is a good choice for contractors when suppliers' capabilities are uncertain. Although a wide range of studies have deployed simulation models to investigate the supply chain and logistics impacts on the success of the projects, few studies used the simulation to generate the incentives and penalties strategies that can motivate the supplier to perform higher reliability.

2.2 Blockchain and Smart Contract in Construction

Blockchain is a continuously growing list of records, called blocks, which are linked and secured using cryptography. It is a decentralized, distributed, shared, and immutable database ledger that stores a registry of assets and transactions across a peer-to-peer (P2P) network [11]. The Smart Contract is a set of computer codes defining the responsibility and risks between two or more parties [14]. It works on an 'if–then' principle, which means if the preconditions were satisfied, then the Smart Contract will enforce the rule executions. Once the Smart Contract is executed, the transaction data, including involved parties, payment amounts, timestamps, and etc., will be secured into a new block and shared in a distributed network. As long as the participants agreed upon the contract clauses, project managers were set free from the time-consuming monitoring, recording, checking, and paying process.

The discussions of the Blockchain and Smart Contract started recently. Mason [15, 14] initially addressed the Smart Contract as a logical extension to BIM whereby the contractual performance itself becomes automated. He argued that the Smart Contract can not be fully automated or can be semiautomated with limited human intervene because the full intelligence of the Smart Contract requires the change of the current social, economic, and law system. The traceability and transparency enable the Blockchain to be an effective tool in supply chain management. The RFID combined with IoT can synchronize the real-time delivery information on Blockchain [11] with the details of the delivered materials, such as original fabricator factories, amounts of arrival, the sequence of arrival, etc. Li et al. [12] conducted a thorough review of the potential Blockchain application in the Architecture, Engineering, and Construction (AEC) industry and used three case studies to demonstrate feasibility. Wang et al. [16] developed a Blockchain platform to detect if the actual delivery of modular components is in accordance with the initial planning in a precast project. Elghaish et al. [5] proposed to use real-time BIM 4D and 5D data to assign incentives and penalties for the crews accordingly. Ahmadisheykhsarmast and Sonmez [3] provided construction contract platform for secure payments by linking Microsoft Project cost and schedule data to the Ethereum Smart Contract. The contract input data requires manual reports which is still time-consuming, costly, and prone to errors. Hamledari and Fischer [8] proposed using reality capture technologies as the input to trigger Smart Contract progress payment. The cast study stays at a conceptual level. Previsou research indicates that there is a great need of further development of Blockchain technology's implementation in the AEC industry. To fill in the gap of knowledge, this research focused on the Smart Contract formulation process, specifically, developing a complete scenario design to generate Smart Contract rules and implementing the rules using the Blockchain techonology to motivate reliable cooperation in construction process.

3 Methods

Figure 1 illustrates the research framework. After collecting modular delivery and onsite installation data from a high-rise residential project in Singapore, we established a STROBOSCOPE simulation model to quantify the impact of PBU delivery variabilities on project schedule and cost. Based on the simulation results, we developed Smart Contract rules to motivate on time delivery. We then built a Blockchain platform to facilitate the execution of the Smart Contract rules. Once the real-time delivery performance is detected and entered into Smart Contract, the corresponding clauses will be triggered, and payments can be assigned automatically.

3.1 Data Collection

The research collected data from a residential building project in Singapore utilizing the modular construction method for PBU installation. Data was collected by one of the authors, who was part of a GC team for this project. Durations of 74 PBU loading platform (PBU_LP) assembly and 139 PBU hoisting activities were collected. The PBU loading platform assembly durations and PBU hoist up durations were fitted using Excel Solver to identify the duration distribution. PBU_LP assembly follows a pert distribution of PERT(50,55,60) with the minimum, most-likely, the maximum value of 50, 55, and 60 min. PBU hoist up follows a gamma distribution of GAMMA(3,6). The project manager estimated that installing a PBU needs 90 to 100 min. Meanwhile, the collected data showed there were 30% chances of rework for PBU_LP and 10% chances of rework for PBU installation. The results were validated by the project managers who worked on the project for the entire project duration.

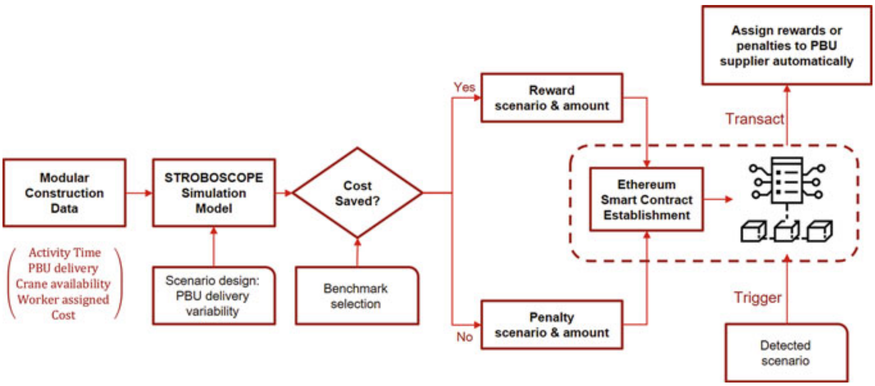

Fig. 1 Research framework

Every week, 18 PBUs were delivered by six trucks. The downloading process took 30 min. Each PBU loading platform was installed in 60 min. Therefore, the sequence of the truck delivery did not have a much impact on installation actictives. Three types of PBUs are identified in this project, which was code as A, B, C. There was large variability in delivery. For instance, in the best scenario, some batches had an equal number of each PBU type. In some worst cases, there were batches supplied 14 A, four B, and zero C.

3.2 Simulation Model

A STROBOSCOPE simulation model was built to understand the impact of delivery on trade productivity and project performance. The building has eleven floors. For the ten floors above the ground, each floor has four apartment units, and each unit requires to install three different types of PBU. As shown in Fig. 2, before working

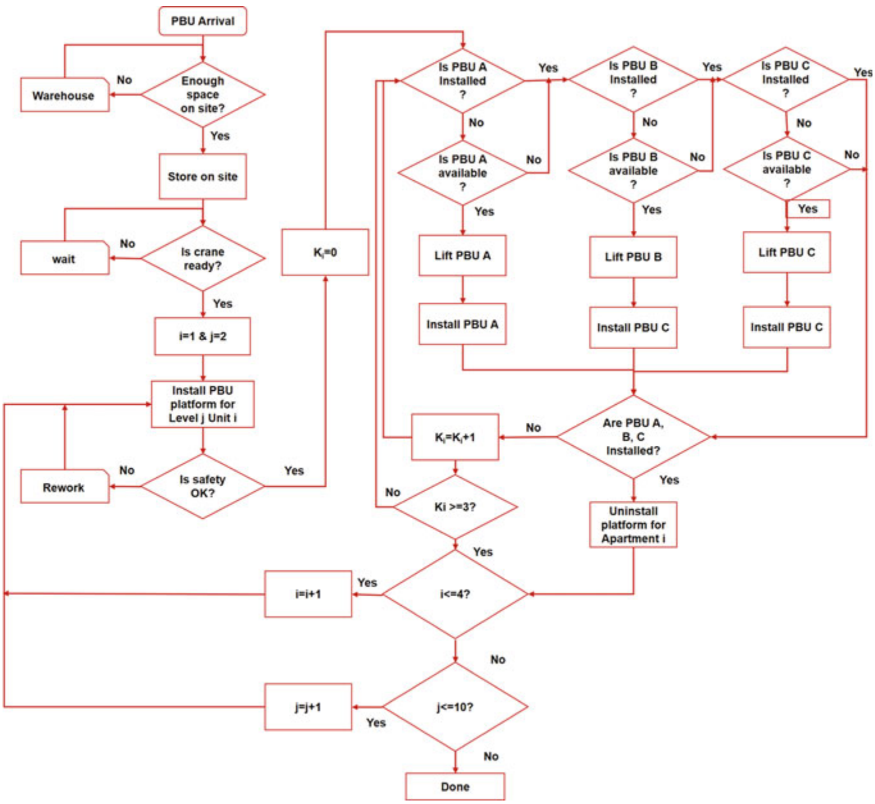

Fig. 2 Simulation flowchart

Table 1 Five scenarios tested with the simulation model

Scenario	Variability
1	[0,6)
2	[6,12)
3	[12,16)
4	[16,22)
5	[22,24)

on each unit, the workers need to install a PBU Loading Platform for safety concerns. Once PBUs were delivered to the job site, they were downloaded and stored on-site if there is enough space. After that, if the crane is ready, PBUs were lifted by the crane and installed by a group of workers. After finishing all 3 PBUs in one unit, the workers dismantled the platform and moved on to another unit one floor above. The workers can work on at most 4 units simultaneously due to safety restrictions. The priority of PBU works is A, B, and C. In the situations when a certain type of PBUs is not available, the crane still hoisted up the available PBUs for the remaining units and then waited until it became available. This process was repeated until all the PBUs were hoisted up. According to observation, the crane was available 70% of the time and five workers were assigned to the project.

The model was executed at five different levels of PBI arrival variabilities. Different levels were measured based on the deviation from the best scenario. For example, when 8 PBUA, 8 PBUB, and 2 PBUC were delivered, the total wrong deliveries (called "variability") are measured as $|8-6| + |8-6| + |2-6| = 8$. In the worst case, when 18 PBUA, 0 PBUB, and 0 PBUC were delivered, the variability was $|18-6| + |0-6| + |0-6| = 24$. The variability can range from 0 to 24.

We use the k-means cluster algorithm to classify into five different variability levels, which is concluded in Table 1. In this research, we assumed the delivery pattern stays consistent for the entire project duration. The simulation model ran 100 times for each of the five scenarios listed in Table 1. The project worked 10 h per day and six days per week. The direct cost were $648,000 for 120 PBUs, $1000/day for operating the crane, and $140/day per worker. The indirect cost was $1500/day.

3.3 Smart Contract Algorithm

The incentives and penalties generated from the simulation results can be programmed in the Smart Contract to promote a higher delivery level. Smart Contract defined the five variability levels based on the simulation results. Project managers suggested using scenario 2 as the benchmark because PBU delivery is the key to project success. The Smart Contract rule is transparent to all the participants on the network, and it can enforce the execution once a certain condition is detected. Smart Contract alleviated the time-consuming work of tracking and paying by automating the consensus algorithms.

Ethereum is a decentralized, open-source Blockchain featuring smart contract functionality, and it is the most widely adopted platform to develop the Smart Contract. This research deployed the Smart Contract in Remix-Ethereum, which is a powerful open-source tool to write Smart Contract straight from the browser. The steps to construct a contract are shown in Fig. 3. In this research, we defined that only the GC can invoke the Smart Contract. The contract requires the GC to input the detected delivery level of the PBU supplier. If the detected scenario is 1, then the corresponding incentives will automatically be assigned to the PBU supplier. If the detected scenario is 3, 4 or 5, the contract will require the PBU supplier to pay the associated amount of penalty.

Algorithm 1: Reward and Penalty Smart Contract

```
Result:  This Smart Contract algorithm can assign rewards or penalties to PBU supplier once
         a certain delivery reliability is detected

Input:   transaction address; delivery reliability(1, 3, 4, 5)

Step 1:  assign address to GC
         assign address to PBU supplier
         /* Address functions as the identification for each
         participant in the Blockchain network. Transactions are send
         to the address directly
Step 2:  Criteria to invoke Smart Contract
         Requires GC to input GC address, PBU supplier address

Step 3:  Function reward (delivery level), only GC can operate
           if (delivery reliability = 1)
             transfer amount_1 Ether to PBU supplier address
         end

         Function penalty (delivery level)
           if (delivery reliability = 3)
             require PBU supplier to pay amount_2 Ether to this Smart Contract
           if (delivery reliability = 4)
             require PBU supplier to pay amount_3 Ether to this Smart Contract
           if (delivery reliability = 5)
             require PBU supplier to pay amount_4 Ether to this Smart Contract
         end
```

Fig. 3 Steps to establishing a smart contract

Table 2 The simulation results of project durations and overheads under different scenarios

			Cost				Monthly payment	
Scenario	Variability	Project duration	Direct	Indirect	Total	Difference	Dollar	Ether[b]
1	[0,6)	40.9	$717,513	$61,335	$778,848	$2,080	$1,221	1.74
2[a]	[6,12)	41.5	$718,618	$62,310	$780,928	$0	$0	0.00
3	[12,16)	45.7	$725,639	$68,505	$794,144	−$13,216	−$6,945	−9.92
4	[16,22)	47.7	$729,073	$71,535	$800,608	−$19,680	−$9,904	−14.15
5	[22,24)	50.8	$734,343	$76,185	$810,528	−$29,600	−$13,987	−19.98

[a]Benchmark scenario; [b]1 Ether = $700 at the beginning of the year 2021

4 Results and Model Validations

4.1 Simulation Results

The simulation results are shown in Table 2. When the variability falls between 0 and 6, the project took 40.9 working days to finish. The benchmark scenario took 41.5 working days to finish. Compared with the benchmark scenario, the variability level 1 can help the project save $2080. Assuming the Smart Contract used the monthly payment (24 working days/month), the supplier should receive $2080/40.9 * 24 = $1221 incentives under this situation. Ether is the cryptocurrency used in the Ethereum Smart Contract. Assuming 1 Ether = $700 based on the rate in the beginning of year 2021, the supplier will receive 1.74 ($1221/700) Ethers in this case.

On the contrary, when the variability falls between 12 and 16, 16 and 22, and 22 and 24, the project took 45.7, 47.7, and 50.8 working days to complete respectively. The results consolidated that the project manager used scenario 2 as the benchmark because the severity on the overall schedule suddenly increases when the variability level exceeds 12. Compared with the benchmark scenario, 9.92, 14.15, and 19.98 Ethers should be assigned as penalties for the monthly payment.

4.2 Smart Contract Testing

Figure 4 shows that there is 100 Ether initiated in each account (red ①). To invoke the Smart Contract, project managers should input the account address of himself/themselves and the PBU supplier. Assuming he or she decides to store 5 Ether when initiating the contract. Then click on the "transact" (red ②). There will be a success mark (red ⑤) once the contract confirmed the correct message sender and contract address. Then, the project manager inputs the delivery variability level. For instance, if the PBU supplier delivers six PBUAs, six PBUBs, and six PBUCs,

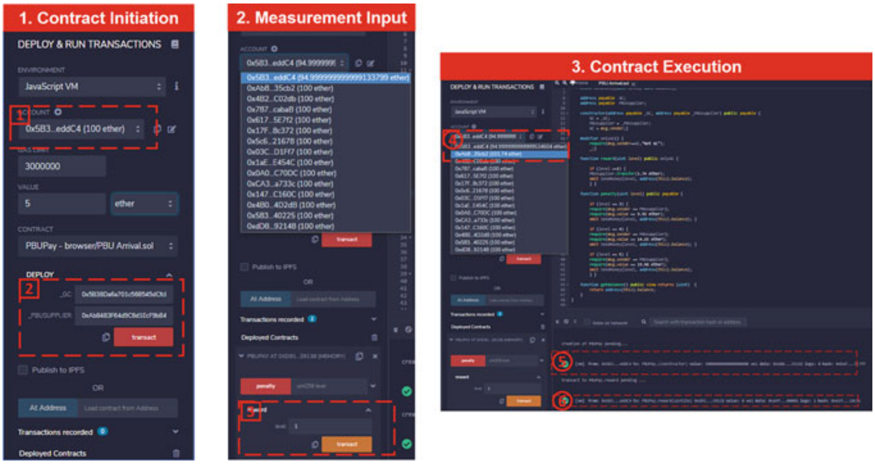

Fig. 4 Smart contract model test

input 1 (red ③), and the Smart Contract will transfer 1.74 Ether to the PBU supplier's account directly (red ④). A successful mark will appear as well (red ⑥). The transaction information will further be hashed and added to a new block, the users in the distributed network can review the information in real-time.

Similarly, the contract requires the PBU supplier to pay a penalty to this contract when the disadvantage scenarios were detected. For instance, when the variability level 5 is detected, the contract will require the PBU supplier to pay 19.98 ether to this Smart Contract. Other behaviors will return the error signal in the Smart Contract network. For example, as shown in Fig. 5, after invoking the Smart Contract, the

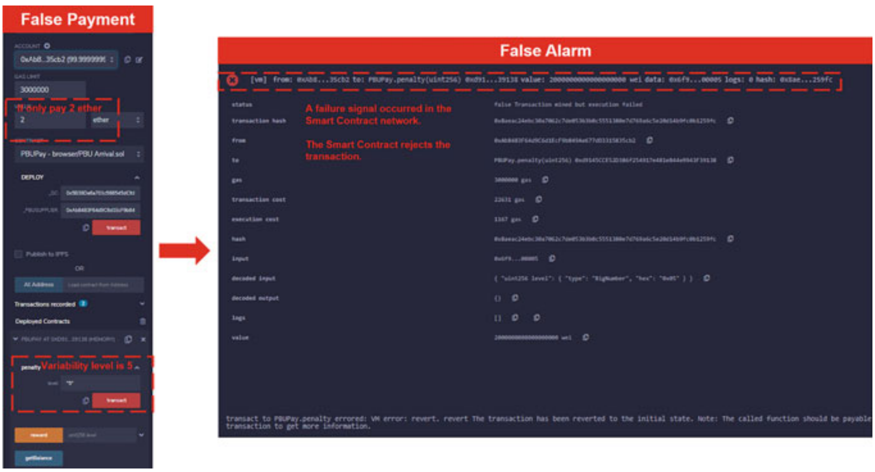

Fig. 5 Failure operation in the smart contract

PBU supplier was required to pay 19.98 Ether when the project manager input “5” for the variability level. The PBU supplier tried to pay only 2 Ether, and then an error signal was returned. Such information can be distributed and synchronized to the Blockchain network, where the participants in the network can view the failure transactions instantly and coveniently. Therefore, no one can manipulate the contract once the detected condition is identified. Such rigorous execution of the Smart Contract enforces the commitment to be performed reliably to enhance the project’s overall performance.

5 Conclusions

This research developed a Blockchain platform to facilitate and motivate reliable delivery for modular construction. The research established a simulation model to understand the impact from various levels of delivery reliability to installation productivity. Smart contract clauses were developed based on the quantified impact so that the implicit knowledge of tracking reliability was transformed into explicit knowledge of cost savings or overrun. As recognized of the importance of necessity of the design of smart contracts for progress payments by previous researches [3, 8], this project provided an incentive-penalize Smart Contract prototype to promote reliable delivery of suppliers based on the customized needs. The enforceability of the Smart Contract enables the execution process and promotes the supplier to perform at a higher level.

The benefits of the findings include three folds. First, it provides objective and instant feedback on the supplier’s performance. In many current practices, subcontractor performance appraisal tends to be subjective and qualitative. It is also difficult to customize the incentives and penalties that can reflect various levels of contributions. Second, the methods developed in this research provide an anchor point to elaborate on and understand the different delivery variability of the PBUs to the overall project schedule. Third, the Blockchain platform can track suppliers’ performance and facilitate Smart Contract execution, which is helpful to alleviate the management time and effort required in the current practice. With the suitable adjustment, the Blockchain platform developed in this research can be customized to other types of modular construction projects.

6 Limitations and Challenges

This research has two limitations. First, the inputs for Blockchain platform need to be verified and entered by the GC. So at the current stage, the Blockchain platform is not a fully decentralized system. Second, only the impact of PBU delivery was included in the simulation. It is recommended to further develop the Blockchain platform to allow all participants enter inputs and consider the impact of participants' completion reliality on project cost and schedule performance.

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The Feasibility of Reuse in the Concrete Industry

Zaineb Al-Faesly and Martin Noël

1 Introduction

This study aims to understand the work being done by Canada's concrete industry in concrete reclamation. Reclamation in this study is further separated into two distinct categories, namely reuse (i.e., repurposing components in their original form with minimal reprocessing) and recycling (i.e., crushing concrete into smaller particles for various uses), to gain a deeper understanding of the degree of concrete reclamation undertaken in Canada. Downcycling refers to a recycling process that leads to a lower value product than the original material. To achieve this objective, an online survey was created and sent to stakeholders involved in the concrete industry. The survey was comprised of four sets of targeted questions for the various professionals involved in the concrete industry from design engineers in the office to contractors in the field. The data collected from the responses was further used to learn about the professionals' perception on the concept of concrete reuse and its associated advantages and disadvantages.

2 Background

All structures inevitably reach their end of life. This can be the result of normal wear-and-tear and deterioration that causes gradual functional obsolescence of structural

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components leading to poor performance, but more frequently structures are decommissioned for other reasons that can include changes in land use or the need for functional improvements. In the latter scenario, a majority of the existing structural components may remain in relatively good condition. Therefore, the construction industry faces an increased need for ensuring the future adaptability of its buildings and infrastructure. This can be done by adopting strategies during the initial design phase that will facilitate future deconstruction of the building elements, which allows for maximum recovery of material resources for a second useful life [1]. This approach is often known as cradle-to-cradle design, where waste from one project becomes a resource for the next—as opposed to the traditional cradle-to-grave design philosophy. Consequently, an industrial ecosystem is needed in which construction materials flow in continuous closed-loop cycles.

2.1 Hierarchy of Waste Management

The WM hierarchy is a guideline to prioritize the methods of using resources to lower negative environmental impacts. The hierarchy provides the priorities for dealing with waste and presents the following actions in order of significance [4]:

1. Reduce the material quantity and waste generation
2. Reuse existing components
3. Recycle materials by adapting waste into reusable secondary materials
4. Generate energy from the waste if permitted
5. Dispose of waste in the most environmentally favourable option

Recycling involves many steps, including component disassembly, material separation, transportation, storage, and processing, all of which produce additional costs and environmental impacts. Hence, reuse is preferable to recycling [6]. As it stands, the highest level that is commonly reached in the Canadian concrete industry is downcycling (e.g., crushing concrete and using it as base aggregate).

2.2 Reuse Versus Recycle

The terms reuse and recycle are sometimes used interchangeably in literature. However, the two are inherently different. Reclaimed materials are those that have been diverted from the waste stream and not disposed in landfills. Reused materials are reclaimed and repurposed in their original form, with minimal reprocessing. They may be cut to size, adapted, cleaned up, or refinished, but they are fundamentally retaining their original form, such as a retaining wall built with concrete blocks that is carefully disassembled, cleaned, stacked on pallets, and eventually used to create a new concrete wall (Fig. 1 on the left). Recycled materials are reclaimed, reprocessed,

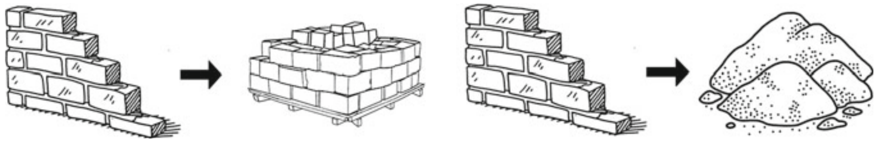

Fig. 1 Examples of concrete reusing (left) and concrete recycling (right)

and remanufactured to form part of a new product; if the new product is of lesser value than the original material, this may be referred to as downcycling. For example, a concrete block wall is knocked down to ground level using a machine, with the broken concrete pieces crushed and screened in a mechanical crusher to create an aggregate substitute.

Reusing materials in their original form has the following benefits:

- Replaces the need for new virgin materials
- Reduces the energy demand for manufacturing new products
- Retains the embodied energy of the material (required to extract, process, manufacture and deliver it)

This offers significant environmental and economic savings [2]. While some of these benefits can also be obtained through recycling, it requires greater energy consumption and often results in low-value products.

2.3 Impact of Construction and Demolition Waste

C&D waste has significant environmental, social, and economic impacts. This harms the environment, contributes to the increase of energy consumption, and slowly exhausts finite landfills resources [9]. Concrete is a fundamental building block of built structures; in fact, it is the most-used construction material worldwide. It is a water demanding material, consuming close to a tenth of the world's industrial water use. It is anticipated that in 2050, 75% of the water demand for concrete production will likely occur in areas that are expected to experience water insecurity [10]. Cement, a key ingredient in concrete, accounts for 8% of global carbon dioxide emissions [8]. Research has shown that recycling C&D waste causes substantial declines in emissions, energy use, global warming potential, and conserves landfills space when compared to disposal of wastes in landfills [9]. Moreover, the price of alleviating the effects of disposal is tremendously high. Consequently, it is crucial to reclaim C&D wastes.

2.4 Previous Work and Research Needs

While the amount of work and research in concrete recycling is extensive and available, finding relevant and comprehensive information on concrete reuse is challenging. Concrete reuse is not a widely adopted concept and thus the research is very limited. European countries do seem ahead in integrating reuse where a reclamation-led approach to demolition and reversable design strategies are being researched in recent years. The European Union has even issued the Waste Framework Directive aiming at reuse instead of recycling [5]. While the text is meant purely as a documentation tool and has no legal effect, it does provide guidance on how to effectively approach waste management. Generally, the projects that integrated reused concrete in their work used it for non-structural applications, like reusing it as concrete tiles, paving, and/or curbs [3], or very limited structural applications, like reusing only panels from prefabricated housing in Finland [7]. In contrast, research to support reuse of steel is much more established with some researchers exploring facilitating greater reuse and recycling of structural steel in the construction and demolition process [6]. The perception of industry professionals on concrete reuse is not clear. However, as discussed in the previous subsections, a paradigm shift is needed to transition to incorporating reclaimed—and more specifically reused—materials into construction projects. Consequently, gaining a clear understanding of the opinions of professionals on concrete reuse and their assessments of its benefits and challenges is a critical step to know what barriers are in the way of shifting to concrete reuse in construction.

3 Research Objective

For this study, a survey was created and dispatched. The survey was created primarily to answer two main questions:

1. What is the current degree of reclamation (recycling and/or reuse) in the concrete industry and why?
2. What is the perception of industry professionals on concrete reuse, including the perceived benefits and challenges of such practice?

4 Methodology and Results

Some of the questions in the survey were inspired by the *Facilitating Greater Reuse and Recycling of Structural Steel in the Construction and Demolition Process* study published in 2006 by researchers at Ryerson University. These questions, originally written for steel, were adapted to the concrete industry and modified to meet the research objectives.

4.1 Classification of Participants

With concrete reuse being a relatively novel concept, it is critical to have a holistic understanding from the various stakeholders in this industry. Therefore, the 125 participants were categorized into four streams of the survey as follows:

- Concrete Professional (e.g., design engineer, consultant, and/or quality control)
- Concrete Structure Owner (e.g., municipality, provincial or federal agency, and/or private owner)
- Concrete Supplier (e.g., precast, ready-mix)
- Concrete Contractor (e.g., builders, demolishers)

The survey was open Canada-wide. Out of 125 total participants only 56 (45%) provided location information with 46 entries noted to be in Ontario. Another 8 were from other Canadian provinces including Quebec (3), Alberta (3), and British Columbia (2). Moreover, since the survey was shared online, there were a few responses from outside of Canada. Of the 56 individuals who provided location information, 2 were outside of Canada, specifically in India and Dubai. The remaining 69 participants opted not to share their location information. Note that sharing personal or professional information was completely voluntary.

The respondents were asked to self-identify within one of the four streams. Each stream had its own set of personalized questions, although certain questions were asked in multiple streams. For the first two streams, Concrete Professional and Concrete Structure Owner, the participants were diverged further based on their response to whether their company or agency had any experience incorporating reclaimed concrete on a previous project. This breakdown is outlined in Fig. 2.

The results of the *Identification* question are shown in Fig. 3. The largest group of respondents identified as the Concrete Professional category, accounting for 78% of the 125 participants. The reason for this domination is likely due to the Concrete Professional category being the broadest category whereas the others were rather specific. Moreover, connecting to professionals in that category to participate in the survey was more accessible due to a stronger LinkedIn presence.

4.2 Concrete Professionals

The Concrete Professional stream includes those who identify as, for example, design engineers, consultants, or quality control personnel. The first question in this stream divided the participants based on whether their company had any experience incorporating reclaimed concrete on a previous project. 83 participants answered this question with 20 (24%) having some experience and 63 (76%) having no experience with reclaimed concrete.

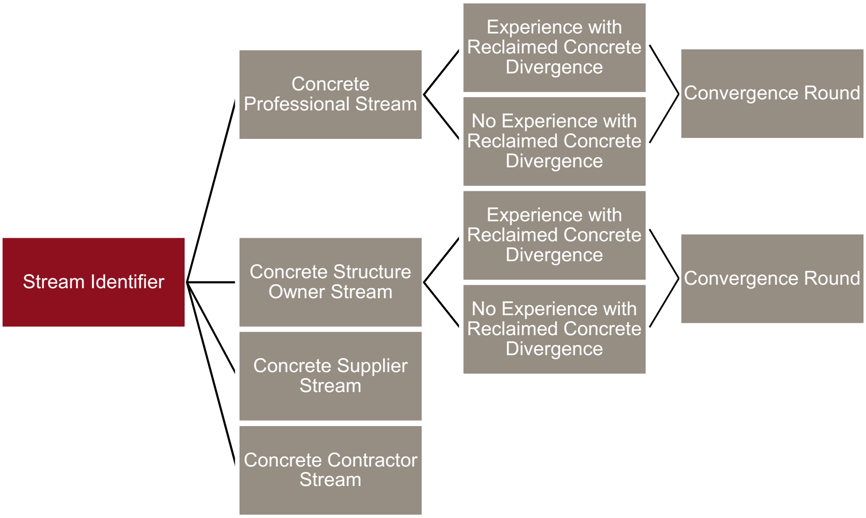

Fig. 2 Breakdown of questions

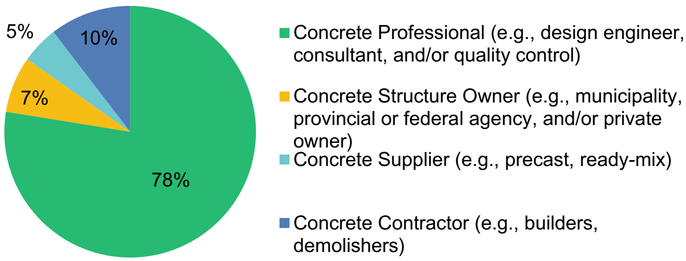

Fig. 3 Breakdown of participants

4.2.1 Previous Experience with Reclaimed Concrete

Participants with experience incorporating reclaimed concrete in past projects were asked specific questions relating to their experience. When asked approximately what percentage of the projects undertaken last year incorporated reclaimed concrete, the average response was 27%. Only 21% of participants with past experience with reclaimed concrete reused 60% of the material or more, and only 7% recycled more than 60%. Most participants reused or recycled less than 20% of the reclaimed concrete from past projects. This suggests that even with conscious efforts to reclaim concrete, most of it still ends up being disposed as waste in landfills.

Participants were also asked about the purpose or application of the concrete that they reclaimed. The top three response were *Base material* and *Non-structural applications*, followed by *Aggregate in concrete*. This demonstrates that reclaimed materials are often downcycled as low-value products and are not fully trusted for structural applications. The participants were later asked if they would consider using reused concrete (i.e., in its original form, not downcycled) in future projects; 10 said "Yes", 0 said "No", and 4 said "Maybe", suggesting a general willingness and openness to the concept of reuse. When asked to elaborate on their reasons, several indicated a perceived financial benefit to concrete reuse. Practicality was also highlighted on two occasions, with one respondent stating that it would be useful in northern communities where it is otherwise difficult to deliver bulk materials like aggregate. However, there does seem to be low confidence in reused concrete for structural purposes, with participants stating it would be useful for barriers and temporary uses and another stating that they would only limit its use to non-structural applications such as boulevards, planters, paver stones, etc. One respondent stated that they need to know more about the quality of the concrete to be reused before moving forward with it.

4.2.2 No Experience with Reclaimed Concrete

Participants with no experience with reclaimed concrete were asked about their thoughts, perceptions, and considerations of the possibility of reusing concrete in future projects. When asked if they would consider using reclaimed concrete (either reused or recycled) on a future project, 27 (48%) said "Yes", 3 (5%) said "No", and 26 (46%) said "Maybe". While the results are promising in the attitude of participants to reusing concrete with the slight sway to "Yes", it is critical to note the approximately 50%–50% split between "Yes" and "Maybe". When asked if they would consider reusing concrete in its original form—not down-cycled as crushed aggregate or base material—for future projects, 34 respondents said "Yes" and 22 replied "No".

4.2.3 Questions for Both Sub-Groups

Both divergences of participants, i.e., with and without experience using reclaimed concrete, were presented with questions focusing on their general perception of concrete reclamation, and more specifically, concrete reuse. Participants were asked to select potential reasons that would lead them to incorporate reused concrete components. 65 professionals responded to this question. As shown in Fig. 4, 75% stated that the *Approval of an engineer* would lead them to consider reused concrete. This suggests that the verification from a trusted professional plays a critical role in the confidence of the reused concrete components. A majority of respondents also selected *Certificate of conformance*, as well as *Financial discount*, suggesting that having a standardized approach to verifying the condition of the components and improving their bottom line are both fundamental to the decision-making process. *LEED credit* was selected by nearly half of the professionals suggesting that this is also an important consideration to industry. For *Other*, many highlighted the need of technical specifications and design provisions to guide them in reusing concrete. Several noted the need for significant research findings, previous successful projects,

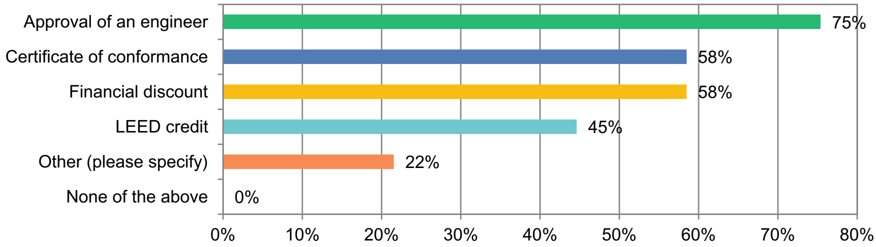

Fig. 4 Breakdown of reasons that would lead professionals to reuse concrete

and testing reports that would support the concept of reuse and establish it in the industry. Others emphasized the need for code approval and client approval to move forward with reuse.

Participants were also asked to rank the main obstacles to the reuse of concrete structural components in construction. The top-rated answer was *Technical challenges*; this was anticipated because as design engineers, consultants, and/or quality control personnel, ensuring good performance is critical. *Liability challenges* and *Logistical challenges* were also both highly rated. The liability concerns were also expected as approving work that contains reused concrete components and taking professional responsibility for it will be daunting for professionals in this category. Logistical obstacles were also predicted as working with existing components will present new constraints for availability and quantity of materials.

4.3 Concrete Structure Owners

The Concrete Structure Owner stream includes those who identify as, for example, municipality, provincial or federal agency, and/or private owner. The first question in this stream divides the participants based on whether their establishment had any experience incorporating reclaimed concrete on a previous project. 8 participants answered this question with 3 (37%) having experience and 5 (63%) having no experience.

4.3.1 Previous Experience with Reclaimed Concrete

Participants with experience accepting reclaimed concrete were asked specific questions relating to their experience. When asked approximately what percentage of the projects undertaken last year incorporated reclaimed concrete, the average answer from 3 participants was 28%. The respondents indicated slightly more experience with recycling than reuse, however the difference was small. Like the previous group, the most common uses for the reclaimed concrete were *Base material* and *Non-structural applications*.

4.3.2 No Experience with Reclaimed Concrete

Participants with no experience with reclaimed concrete were asked about their thoughts, perceptions, and considerations of the possibility of reusing concrete in future projects. When asked if they would consider using reclaimed concrete (either reused or recycled) on a future project, 3 (75%) said "Yes" and 1 (25%) said "Maybe". This demonstrates a positive outlook to the concept of reusing concrete. When the participants were further asked about their reasoning, 3 offered comments. One professional said they would consider it but would have to familiarize themselves with case studies, pros/cons, etc. A second professional voiced that code compliance would be a key issue but as long as it meets applicable standards and specifications, they see no issue. The last professional stated that they are supportive of the concept because it reduced construction waste from demolitions and the extensive use of natural aggregates.

The next question specifically asked if they would consider reusing concrete in its original form (not down cycled as crushed aggregate or base material) for future projects. Interestingly, the percentages reversed with 1 (25%) saying "Yes" and 3 (75%) saying "Maybe". This portrays a significant level of uncertainty in the concept of reused concrete from an owner's perspective.

4.3.3 Questions for Both Sub-Groups

Both divergences of participants, i.e., those with and without experience using reclaimed concrete, were presented with questions focusing on their perception of concrete reclamation, and more specifically, concrete reuse. Participants were asked to quantify how often they estimate that a concrete structure is demolished before it is obsolete (i.e., before the end of its functional or structural service life). 7 professionals answered this question with an average response of 54%. This implies that 54% of decommissioned structures can still offer value. The distribution of their responses is shown in Fig. 5.

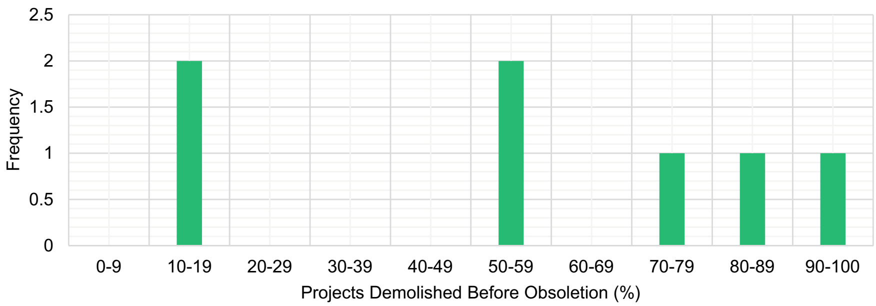

Fig. 5 Distribution of respondents' estimates of structures demolished before obsoletion

Participants were then asked if they consider reuse of structural concrete components for new construction projects to be feasible. There was a 50%–50% split with 3 saying "Yes" and 3 saying "No"—1 person also responded "I don't know". Participants were asked to rank what they viewed as the main obstacles to the reuse of concrete structural components in construction. The same top three challenges were identified as the previous group, but in a slightly different order. Concrete structure Owners ranked *Liability* as their top concern, which makes sense since owners share the heavy responsibility of safety. *Technical challenges* came in second place and *Logistical challenges* at third place.

The participants were then asked to select potential advantages of incorporating reused concrete components in construction. No one believed that that *There are no benefits* as this option had 0 votes. *Reduced consumption of non-renewable resources* was the top-rated advantage, and *Less burden on landfills* came in second. *Economic benefits* was voted as the third-place advantage.

The Owners were also asked about their perception of the quality and performance of reused structural concrete components. None of the respondents believed that reused concrete's quality and performance *cannot be determined* or that it is *likely to be similar to newly constructed components.* 2 respondents believed that it *can be determined, but highly variable.* Another 2 believed that it is likely to be *marginally inferior to newly constructed components.* However, 3 structure owners believed that it would *likely be significantly inferior to newly constructed components.*

4.4 Concrete Suppliers

The Concrete Supplier stream includes those who identify as, for example, precast or ready-mix suppliers. 6 participants identified as a supplier with only 2 providing complete entries. A qualitative analysis of their responses is outlined below. The suppliers were asked how much concrete they deal with per year in metric tons. 3 respondents answered this question giving an average of 78 metric tons (2 stated 100 metric tons and 1 stated 35 metric tons). When asked if they currently provide any products or services that incorporate reclaimed concrete, 4 suppliers answered. Half said they have *No experience with reclaimed concrete*, 1 said they have *Experience with recycled concrete aggregates only*, and 1 said they have *Experience with both recycled and re-used concrete.* None had *Experience with re-used concrete only.* None of the suppliers reused or recycled more than 20% of their concrete.

Suppliers were then asked if they would consider supplying reused concrete products if there was market interest from their clients and an accessible inventory. 3 said "Yes" and 1 said "No". When they were asked to estimate the average markdown in price for reused products, all of the respondents replied *No, there are no discounts provided*. When asked about their reasoning two cited processing costs, explaining that the cost of reclaiming, inspecting, and storing reused product would not lower the cost over making it new, and one stated the fact that using recycled materials could be viewed as a possible value-added product.

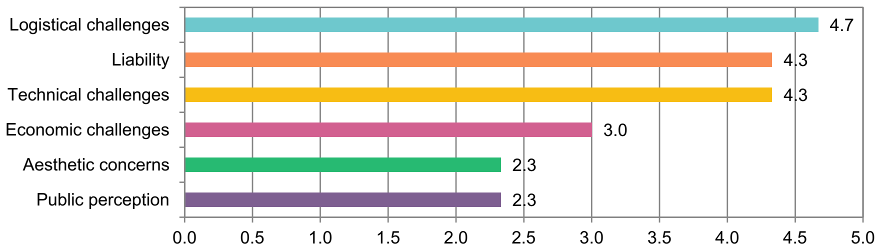

Fig. 6 Ranking of obstacles to concrete reuse

Participants were asked to rank the main obstacles to the reuse of concrete structural components in construction. Like the previous groups, the Concrete Suppliers also listed *Logistical challenges*, *Liability*, and *Technical challenges* as the top obstacles. However, the ranking of the top three differed. Undoubtedly for a supply company, *Logistical challenges* came in as the number one obstacle. *Liability* and *Technical challenges* were tied for second place (Fig. 6). When inquired further if there were other obstacles they wished to share, one person stated the challenges of reclaiming product without damage and another cited the difficulty of maintaining a stable source of the products to ensure quality and availability.

The suppliers were also asked about some of the advantages of incorporating reused concrete components in construction. All 4 participants who answered this question selected *Reduced consumption of non-renewable resources*. 3 participants noted *Reduced greenhouse gases* and 2 participants also ticked *Less burden on landfills*. 25% see some financial and business benefits.

Finally, the suppliers were asked about their perception of the quality and performance of reused structural concrete components. 3 (75%) stated that it *Can be determined, but highly variable* and 1 (25%) stated that it is *Likely to be significantly inferior to newly constructed components.*

4.5 Concrete Contractors

The Concrete Contractor stream includes those who identify as, for example, builders or demolishers. 13 participants identified as a contractor with 7 providing complete entries. The contractors were asked to quantify how much concrete is reclaimed by their company per year in metric tons. The average value from 7 participants was 36 metric tons of reclaimed concrete per company. The breakdown of this reclaimed concrete is presented in Fig. 7. Among all the respondents, less than 20% of the concrete is reused. Less than one-third of respondents recycle more than 20%, while the rest is disposed of in landfills. Only one participant elaborated on their “Other” entry for which they stated, “Waste Disposal”.

Subsequently, the contractors were asked about the purpose(s) or application(s) of concrete reclaimed from their job sites. Similar to the other groups, the reclaimed

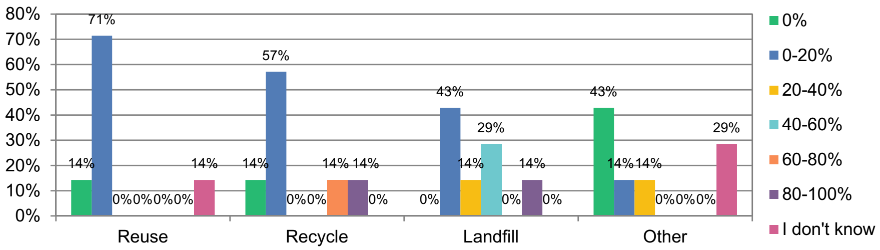

Fig. 7 Breakdown of concrete recovered

concrete materials were primarily used for non-structural purposes. *Base material* was the top response followed by *Non-structural applications.*

The participants were also asked to estimate what percentage of concrete components in a decommissioned structure are likely to be salvageable with minimal processing. 3 contractors said 0–20%, 2 contractors said 20–40%, 1 contractor said 60–80%, and 1 said I don't know. Afterwards, contractors were asked whether there is an additional cost associated with dismantling (i.e., disassembling) versus demolishing (i.e., destroying). 86% stated "Yes" demonstrating that there is certainly an additional cost to be expected with deconstruction when the intent is to salvage components for reuse.

The contractors were asked to comment on the challenges associated with dismantling versus demolition of concrete structures. There was general agreement that this process would be more time consuming, more financially costly, and more labour intensive than regular demolition.

Finally, the contractors were asked about some of their perceived advantages of incorporating reused concrete components in construction. The participants seemed to be clear on the environmental benefits of reuse, however, the financial benefits were less pronounced. The respondents all agreed that there exist benefits in the reuse of concrete that should be explored.

4.6 Additional Comments and Feedback

Participants from all streams were presented with an opportunity to provide additional comments. Twenty-three responses were gathered. Most of the commentators mentioned that they supported this research initiative, with some stating that this topic should be addressed on a larger scale and that they believe the future of construction materials needs to stem from reclaimed materials. There were several who provided further insight. One person working in the concrete pipe industry explained that work is often conducted with little care and damage is frequent, hinting that material recovery is unlikely. Another person mentioned that some articles or a subsection in the National Building Code of Canada (and the Canadian Highway Bridge Design

Code), as well as corresponding provincial building codes, should be added to introduce the idea, make recommendations, and pave the way for future use of reclaimed building components.

One comment emphasized that while reusable concrete might be a very good option, it cannot gain acceptance before clear guidelines are available. They echoed the liability concerns stating that no contractors nor engineers would want to take on the risk of using old, recycled concrete on their projects. They further explained that insurance is expensive in the construction and design practice, hence, everyone is afraid to take risks. Another professional stated the need for proper procedures to be prepared and submitted to the engineering and construction crews about concrete reclamation explaining that often when concrete is poured on site, any excess is simply put into waste disposal bins for hauling off site. Therefore, reuse of existing concrete can be an economic and environmental benefit only if proper knowledge is shared with those that actually make the calls on site (i.e., site superintendents).

Another comment expressed positivity by stating that structurally speaking, it is not difficult to assess recycled/reused components. However, it is the durability and life cycle side that is critical and that can be ambiguous explaining that if over a 75-year lifecycle it is shown the reused components are financially superior when considering rehabilitation, maintenance, and eventual replacement then it would be a very interesting prospect to consider. The participant also questioned the availability of components and where they will be stored. They also inquired about the potential need for warranties or guarantees on these products, as well as ensuring sufficient supplies for a given project. Lastly, it was asked whether the geometry suits the site, or can the site be modified to suit the geometry of the components.

5 Conclusions

This survey study presented several significant outcomes that are summarized below:

- Unanimously across all four streams, no professional believed that there are no benefits to incorporating reused concrete components in construction
- The environmental advantages of concrete reuse appear very clear to all four streams; however, financial benefits, while acknowledged, are less pronounced
- The same three main obstacles to concrete reuse emerged across the three streams where this question was asked: technical challenges, logistical challenges, and liability challenges. However, the order was different depending on the stream:
  - For the Concrete Professional stream, technical challenges were first
  - For the Concrete Owner stream, liability concerns were first
  - For the Suppliers stream, logistical challenges were first
- All contractors surveyed—except those who stated they don't know—assert that there is an extra cost to dismantling versus demolishing as it is more time consuming and labour intensive

- There is positive interest in the concept of concrete reuse; however, there is apparent uncertainty on how to approach it and thus there is a need for guidance
- A successful approach to concrete reuse is one that involves all parties involved on- and off-site, including engineers, consultants, contractors, suppliers, site administrators, and of course, the client.

While there is positive interest in the concept of concrete reuse, there is clear uncertainty on how to approach it and, thus, there is a need for practical guidance. Future research is required to address the various technical, logistical, and liability concerns of concrete reuse in a comprehensive and holistic manner.

Appendix

In this appendix, the survey questions are provided (edited for brevity).

Part 1: Stream Identifier

- *Concrete Professional (e.g., design engineer, consultant, and/or quality control)*
- *Concrete Structure Owner (e.g., municipality, provincial or federal agency, and/or private owner)*
- *Concrete Supplier (e.g., precast, ready-mix)*
- *Concrete Contractor (e.g., builders, demolishers)*

Part 2A: Concrete Professional Stream

With experience incorporating reclaimed concrete on a previous project:

- Approximately what percentage of your projects in the last year have incorporated reclaimed concrete?
- Approximately what percentage of the reclaimed concrete was:
  - *Re-used (i.e., in its original form)*
  - *Down-cycled (i.e., crushed and used as aggregate or base material)*
- For what purpose(s) or application(s) did you use reclaimed concrete? Check all that apply:
  - *Base material*
  - *Aggregate in concrete*
  - *Non-structural applications (e.g., drainage)*
  - *Residential construction (e.g., apartment building)*
  - *Commercial construction (e.g., office space or warehouse)*
  - *Public infrastructure*
  - *I don't know*
  - *Other (please specify)*
- Was the original source of the reclaimed concrete known? If yes, please specify.

- Would you consider using reused concrete (i.e., in its original form, not down-cycled) in future projects? Why, why not, or why maybe?
- Are you aware of any technical documents (i.e., standards, codes, guidelines etc.) related to the re-use of concrete? If yes, please specify.

Without experience incorporating reclaimed concrete on a previous project:

- Would you consider using reclaimed concrete (either re-used or recycled) on a future project? Why, why not, or why maybe?
- Would you consider using re-used concrete in its **original form** (not down-cycled as crushed aggregate or base material) for future projects? Why, why not, or why maybe?

Both subgroups:

- Do you consider re-use of structural concrete components in an acceptable condition for new construction projects to be feasible? Why or why not?
- Which of the following, if any, would lead you to make use of re-used concrete components?
  - *Approval of an engineer*
  - *Financial discount*
  - *Certificate of conformance*
  - *LEED credit*
  - *None of the above*
  - *Other (please specify)*
- How much on average do you estimate the total design and construction cost of a reinforced concrete structure would increase if it were intentionally designed for disassembly so that its components could be re-used in the future?
- In your view, what are the main obstacles to the re-use of concrete structural components in construction? Please place **most challenging first** and **least challenging last**.
  - *Technical challenges*
  - *Logistical challenges*
  - *Economic challenges*
  - *Aesthetic concerns*
  - *Liability concerns*
  - *Public perception*
  - *Other (please specify)*
- What would be some of the advantages of incorporating re-used concrete components in construction?
  - *There are no benefits*
  - *Reduced consumption of non-renewable resources*
  - *Reduced greenhouse gases*
  - *Economic benefits*

- *New business opportunities/revenue streams*
- *Less burden on landfills*
- *I don't know*
- *Other (please specify)*

- In your view, what type, if any, of structural concrete application would be most suitable for re-use? Which is least suitable? Please place **most suitable first** and **least suitable last**.
  - *Building construction*
  - *Dams and canals*
  - *Bridge infrastructure*
  - *Concrete pipes and culverts*
  - *Hydro poles and utilities*

Part 2B: Concrete Structure Owners Stream

With experience incorporating reclaimed concrete on a previous project:

- Approximately what percentage of your projects in the last year have incorporated reclaimed concrete?
- Approximately what percentage of the reclaimed concrete was:
  - *Re-used (i.e., in its original form)*
  - *Down-cycled (i.e., crushed and used as aggregate or base material)*
- For what purpose(s) or application(s) did you use reclaimed concrete? Check all that apply:
  - *Base material*
  - *Aggregate in concrete*
  - *Non-structural applications (e.g., drainage)*
  - *Residential construction (e.g., apartment building)*
  - *Commercial construction (e.g., office space or warehouse)*
  - *Public infrastructure*
  - *I don't know*
  - *Other (please specify)*
- Was the original source of the reclaimed concrete known? If yes, please specify.
- Would you consider using reused concrete (i.e., in its original form, not down-cycled) in future projects? Why, why not, or why maybe?

Without experience incorporating reclaimed concrete on a previous project:

- Would you consider using reclaimed concrete (either re-used or recycled) on a future project? Why, why not, or why maybe?
- Would you consider using re-used concrete in its **original form** (not down-cycled as crushed aggregate or base material) for future projects? Why, why not, or why maybe?

Both subgroups:

- How often do you estimate that a concrete structure is demolished before it is obsolete (i.e., before the end of its functional or structural service life)?
- Do you consider re-use of structural concrete components for new construction projects to be feasible?
- In your view, what are the main obstacles to the re-use of concrete structural components in construction? Please place **most challenging first** and **least challenging last**.

  – *Technical challenges*
  – *Logistical challenges*
  – *Economic challenges*
  – *Aesthetic concerns*
  – *Liability concerns*
  – *Public perception*
  – *Other (please specify)*

- What would be some of the advantages of incorporating re-used concrete components in construction?

  – *There are no benefits*
  – *Reduced consumption of non-renewable resources*
  – *Reduced greenhouse gases*
  – *Economic benefits*
  – *New business opportunities/revenue streams*
  – *Less burden on landfills*
  – *I don't know*
  – *Other (please specify)*

- What is your perception of the quality and performance of re-used structural concrete components?

  – *Cannot be determined*
  – *Can be determined, but highly variable*
  – *Likely to be significantly inferior to newly constructed components*
  – *Likely to be marginally inferior to newly constructed components*
  – *Likely to be similar to newly constructed components*

Part 2C: Concrete Suppliers Stream

- How much concrete approximately do you deal with per year (metric ton)?
- Do you currently provide any products or services that incorporate reclaimed concrete?
- If yes to the previous question, approximately what percentage of the reclaimed concrete was:

  – *Re-used (i.e., in its original form)*
  – *Down-cycled (i.e., crushed and used as aggregate or base material)*

- If there was market interest from your clients and an accessible inventory, would you consider supplying re-used concrete products?
- If yes, what do you estimate the average markdown in price would be (if any)? If not, why so?
- In your view, what are the main obstacles to the re-use of concrete structural components in construction? Please place **most challenging first** and **least challenging last**.
  - *Technical challenges*
  - *Logistical challenges*
  - *Economic challenges*
  - *Aesthetic concerns*
  - *Liability concerns*
  - *Public perception*
  - *Other (please specify)*
- What would be some of the advantages of incorporating re-used concrete components in construction?
  - *There are no benefits*
  - *Reduced consumption of non-renewable resources*
  - *Reduced greenhouse gases*
  - *Economic benefits*
  - *New business opportunities/revenue streams*
  - *Less burden on landfills*
  - *I don't know*
  - *Other (please specify)*
- What is your perception of the quality and performance of re-used structural concrete components?
  - *Cannot be determined*
  - *Can be determined, but highly variable*
  - *Likely to be significantly inferior to newly constructed components*
  - *Likely to be marginally inferior to newly constructed components*
  - *Likely to be similar to newly constructed components*

Part 2D: Concrete Contractors.

- How much concrete is reclaimed by your company per year (metric ton)?
- Where does the concrete you recover go?
  - *Reuse*
  - *Recycle*
  - *Landfill*
  - *Other (please specify)*
- For what purpose(s) or application(s) did you use reclaimed concrete? Check all that apply:

  - *Base material*
  - *Aggregate in concrete*
  - *Non-structural applications*
  - *Residential construction*
  - *Commercial construction*
  - *Public infrastructure*
  - *I don't know*
  - *Other (please specify)*

- What type of establishments are your main customers? Please place **most popular customers first** and **least popular customers last**.

  - *Private sector companies*
  - *Government establishments*
  - *Small-scale local projects*
  - *Large-scale projects*
  - *Other*

- What percentage of concrete components in a decommissioned structure are likely to be salvageable with minimal processing?
- Is there an extra cost to dismantling (taking apart/disassembling) versus demolition (destroying/destructing)?
- What challenges are associated with dismantling versus demolition of concrete structures?
- What would be some of the advantages of incorporating re-used concrete components in construction?

  - *There are no benefits*
  - *Reduced consumption of non-renewable resources*
  - *Reduced greenhouse gases*
  - *Economic benefits*
  - *New business opportunities/revenue streams*
  - *Less burden on landfills*
  - *I don't know*

- Do you know of any projects which featured reuse of concrete components? If yes, please specify.

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Lessons Learned from the Development of an Immersive Virtual Reality (IVR) Game for Construction Safety

Harsh Shah and Zia Din

1 Introduction

The continued availability of skilled workers in the construction sector is a growing concern. According to the Bureau of Labor Statistics, the median age of construction professionals was 43 years. Around 5000 professionals were above the age of 45 years in 2019 [3]. The statistical trends propose challenges to train novice individuals in the industry and transfer expert knowledge to industry successors. Various technologies can play a crucial role in transferring the knowledge to the next generation. Innovation has been a basis for various industries to progress; one such innovation is the use of IVR-based technology; Immersive Virtual Reality (IVR) offers a uniquely immersive and intuitive visualization. Researchers found that IVR helped users perform design and construction reviews [10].

Over the last decade, Augmented Reality (AR), Virtual Reality (VR), and Mixed Reality (MR) have been extensively used for entertainment and video games. However, in recent years, education through AR and VR has found its way. Virtual and Augmented Reality has a promising future for modern-day education [5]. Many researchers have documented its effectiveness in different sectors. For example, in a report on 41 industries, including communications and IT services, music industry, retail industry, education sector, manufacturing industry, real estate industry, and automotive aftermarket, the authors of the report measured the impact of VR, AR, and MR on each sector. They reported increased productivity, improved sales, enhanced learning, and replacement of conventional communication methods [13].

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Simulations in the IVR environment can offer benefits in new workers' training. Use of IVR technologies has been found helpful in improving safety training, such as in underground hazard identification training [15]. Chalhoub and Ayer [4] studied the use of MR for electrical conduit installation in one study, and they found it effective compared to the traditional information delivery method. In another study, Lovreglio et al. [16] explored Virtual Reality's effectiveness in fire extinguisher safety training compared to non-interactive video-based training. The results showed that VR training helped users perform better than users who used other training methods in knowledge acquisition and retention. In another study, researchers introduced an AR-based learning concept in the heating, ventilation, and air conditioning industry [2]. The study was focused on the learning experience and learning outcomes of users.

Moreover, the use of Augmented and Virtual Reality expands to the medical sector as well. Researchers found that AR and VR could be useful approaches with cautious utilization in health sciences and medical anatomy [20]. The findings confirmed that those who received VR training learned faster and better than those who learned through video tutorials.

Similarly, IVR-based simulation is used for forklift training, which offers users many advantages to improve productivity and maintain workplace safety [29]. In addition, a platform, Language Room, provides opportunities to learn new languages in a virtual environment [28]. In one VR-based teaching application, Daydream labs developed an interactive learning experiment aimed at teaching coffee making. Students were either allowed to practice it in VR or shown a YouTube tutorial on pulling espresso shots. The findings confirmed that people who received training in VR learned faster and better than those who learned through video tutorials. Hence it was proved that VR improved productivity [17]. Thus, researchers believe that Virtual Reality can be a useful educational tool [12].

1.1 IVR and Hazard Identification in Construction Work

Hazard identification is a critical component in preventing injury or illness on a construction site. If hazards are not identified, they cannot be appropriately mitigated, resulting in adverse site safety situations. Therefore, the Occupational Safety and Health Administration (OSHA) developed a hazard identification training tool [22]. This is an interactive game-based online training tool for small business owners, workers, and others interested in learning the basic hazard identification concepts. However, the tool does not support an IVR environment, and no data are available on its extent of use and effectiveness.

IVR-supported learning environments are not always effective. Therefore, before implementing a full-scale solution, a pilot study must be carried out. For example, in one study, researchers tested participants' welding skills after an hour-long gas metal arc welding training using VR technology. The findings showed that VR technology did not improve participants' performance scores when compared with alternative training methods [33]. Therefore, in the construction industry, which is traditionally reluctant to adopt new technologies, investing in new IVR training technologies may not seem a sound investment decision. Therefore, proof of effectiveness can help strengthen the case for using IVR games as a tool for hazard identification.

This paper documents guidelines for non-programmers to design applications for teaching or training purposes. The paper's research objectives are as follows. (1) Identify and report the process of developing 3D serious games for construction safety; (2) Identify and report the steps for visualizing 3D serious games in the IVR environment.

2 Methodology

The authors conducted an extensive literature review and observed a lack of adequate game development guidelines for non-programmers, such as instructors and construction professionals who want to develop IVR tools for teaching and training. This paper fills this gap by identifying resources needed for IVR-based serious game development for construction-related activities. Previous work by Din and Gibson [7] helped the authors to search for databases and find different game engines available for game development. The authors studied the Unity game engine and Unreal game engine and compared their suitability for non-programmer game developers.

Also, the authors explored various online learning sources to understand how to learn using game engines. The learning resources include Unity forum [6, 32], LinkedIn Learning [1, 11], and learning resources uploaded by various YouTube content creators like Valecillo (2020), [30]. The overall game development process is explained in Figure 1.

2.1 Game Development Process

Figure 1 shows the design of an IVR game for learning.

In the following sections, the main steps mentioned in the flow chart are described in detail.

2.1.1 Pre-design

The pre-design step begins with identifying learning objectives and end goals. Next, the game development planning phase starts with gathering the resources required for a VR-enabled game. The planning process includes choosing game engine software, finding hardware requirements, establishing a testing plan, preparing a storyboard, and beginning game development.

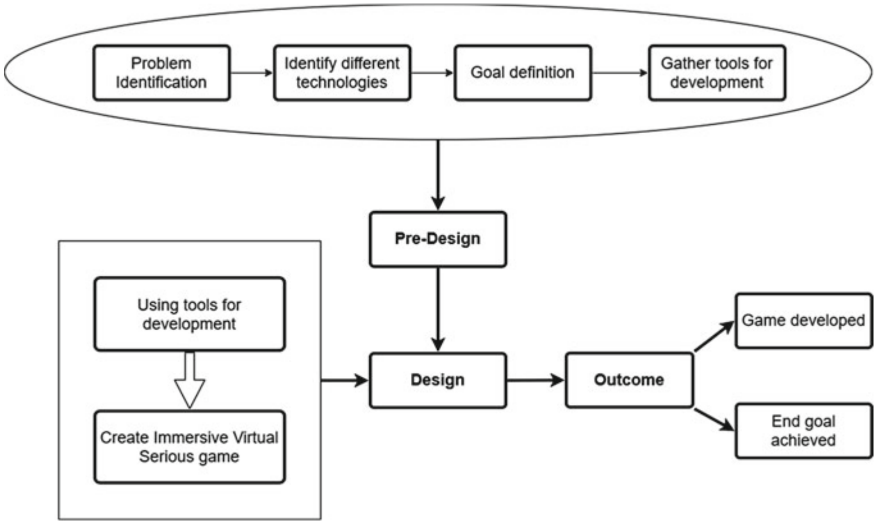

Fig. 1 Steps for designing of immersive virtual reality game (adapted from Checa and Bustillo [5])

2.1.2 Design Development

This phase utilizes the gathered resources and tools to develop a functional game. The game was created in this study using the Unity 2019.4.1f1 (LTS) version. SketchUp [26] was necessary for the authors to build prefab objects for the game. First, the models of tower cranes, power lines, crew members, and temporary site offices as prefab units were obtained from the three-dimensional (3D) warehouse in SketchUp. Then, those individual units were exported from SketchUp as fbx files. Fbx is a filename extension for the filmbox (.fbx) type of file, and it is used to provide interoperability between digital content creation applications [19]. For the rest of the resources, the Unity Asset store was used.

Figure 2 shows the workflow of creating the game environment that can be further divided into the following steps. (1) Setting up the terrain; (2) Placing main components of the game environment such as the building structure and construction equipment; (3) Adding details such as models of site offices, crew members, fences, streets, and surrounding areas to give it a realistic look; (4) Animating various assets in the game; (5) Creating a user interface for players to interact with the game using canvas and buttons to show information.

In this study, the authors present lessons learned for future educators and researchers to support their effort for IVR-based learning content development.

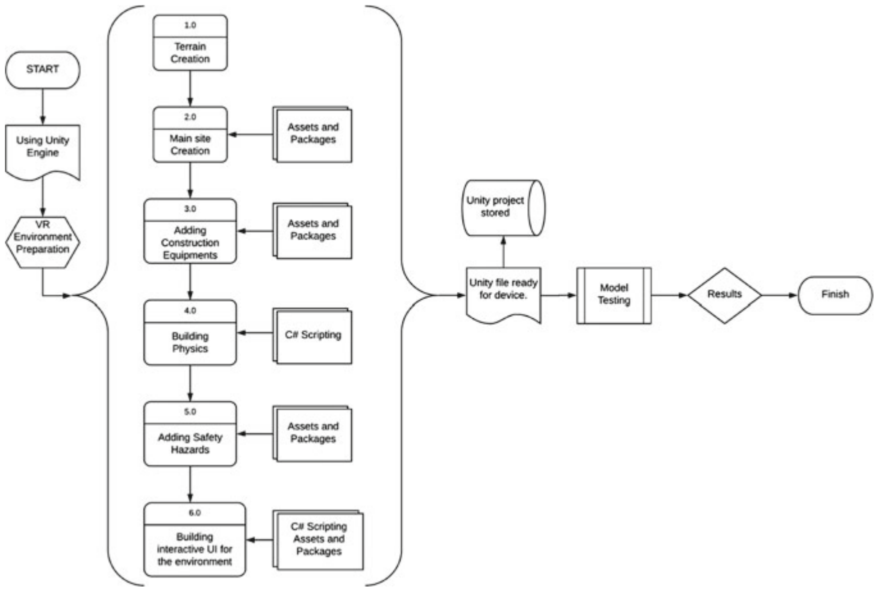

Fig. 2 Game development workflow

2.1.3 Outcome

The game was developed for experiments that are part of ongoing research. The authors tried to create a proof-of-concept VR-based serious game for hazard identification. A few images from the game are shown in Figures 3, 4 and 5. The outcome of this research is workflows for developing a functional game.

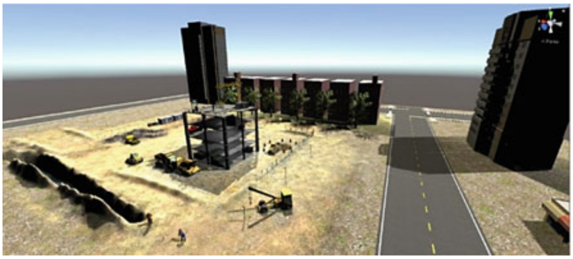

Fig. 3 Screenshot of the construction site scene

Fig. 4 Screenshot of the interactive question panel

Fig. 5 Trigger to interact with the scene to identify hazards and controls

2.2 *Lessons Learned*

2.2.1 Game Development Training

There is a scarcity of information available for developing a safety-focused game in a Virtual Reality setting. The available learning materials had to be modified to suit the project's requirements. The authors completed online courses such as VR Best Practice [32] and Design, Develop and Deploy for VR [6] from the Unity platform, and Virtual Reality Foundations from LinkedIn Learning [1], and consulted various tutorials from YouTube [31]. These tools provided the authors with the requisite information and skills to implement the game development process.

2.2.2 Game Development Engine

There are numerous game development engines available. The authors compared the two most common game engines, Unreal Engine 4 and Unity. The latter was used for development. Table 1 provides a comparison between the game engines based on the work of Gajsek [9].

Table 1 Comparison of game engines

Game engine	Unity 3D	Unreal engine 4	Comments
Platform	It supports across Windows PC, Mac, and Linux platforms. It supports mobile platforms such as Android, iOS, and Windows Phone. Unity also supports consoles: PS4, Xbox One, Nintendo Switch, and Google Stadia. It also supports AR/VR devices and Smart TV	It supports Windows PC, PlayStation 5, PlayStation 4, Xbox Series X, Xbox One, Nintendo Switch, Google Stadia, macOS, iOS, Android, AR, VR, Linux, SteamOS, and HTML5	Unity supports more platforms (offers Smart TV support) compared to Unreal 4. The applications built in one platform can be deployed to multiple platforms
Interface	The interface is easy to use	Comprehending the software requires some practice	Unity is easy to learn for beginners because of the simple interface
Graphics	Suitable for 2D and 3D game development	Mostly for 3D game development	Unreal can create high-quality graphics for all platforms
Supported languages	Utilizes C# scripting and includes a visual scripting environment for non-programmer game development	Uses C++ programming language and provides blueprints for non-programming game development	C# script is considered better as C++ requires the developer to deal with pointers and memory allocation, which can be difficult as a beginner
Game assets	Provides Asset Store containing packages and assets such as building models, construction machinery	Offers Marketplace providing game-ready content and codes	Unity Asset Store has content for creating roleplaying games and packages of pre-programmed assets developed by freelancers and professionals. Available for free or purchase
Pricing	Requires paid personal plan for earnings over $100,000 annually; Additional three more plans for higher-earning limits	Requires 5% royalty when earning is $3000 and above per quarter per game	Both are available free of charge for educational and noncommercial use

The comparison is based on the authors' point of view and game development literature. A careful selection of the game engine is critical for the game's development. The authors choose the Unity engine due to pricing, skill level, scripting requirements, learning resources, hardware requirements, flexibility to build for VR compatible device, and ease of use.

2.2.3 Hardware Used for Development

Hardware configurations and specifications play a crucial role in the game engine's smooth functioning. The following computer system was used for IVR game development to run Unity 3D: MSI GF65 Thin 9SD with System Type of ×64-based PC with Intel(R) Core (TM) i7-9750H CPU @ 2.60 GHz, 2601 MHz, 6 Cores, 12 Logical Processors. The hardware includes Micro-Star International Co. Ltd. MS-16W1 REV:1.0 Motherboard, 32.0 GB installed physical memory (RAM), NVIDIA GeForce GTX 1660 Ti 6 GB, and 512 GB HP SSD EX920.

2.2.4 Programming

To develop a serious game for a VR device, a developer requires to have some programming skills. The authors learned C# scripting from Unity 3D 2019 Essential Training offered by Henri [11]. The authors adapted their knowledge to meet the game development requirements.

2.2.5 Using Assets and Prefabs

Integrating ready-to-use assets and prefabs helps a game developer develop the game swiftly. The assets listed below were free to use on the Unity Asset Store at the time of development.

- **Construction Site Pack**: Alex McDonnell's asset pack includes orange safety barrels that can be placed in various positions in the game scene [18].
- **Sci-Fi Environment**: The Highground Assets developed an asset pack that contains prefabs modular buildings, and this pack was used in the main scene [24].
- **Polygrunt—construction vehicles**: This asset pack was used to include prefabricated dump trucks, bulldozers, cranes, and cement mixtures [23].

  Nature materials vol. 2: This asset pack was used to apply materials to the game's terrain [21].

- **Simple city pack plain**: This asset provided some background units as part of the city [25].

- **Material user interface (UI) package**: Using Material UI helped the authors create an interactive panel with different buttons for answering questions. This package was obtained from GitHub.
- **Extended-Reality (XR) packages provided by Unity**: XR packages are the most important packages for AR, VR or MR projects. Three main packages, namely XR Plugin Management version 3.2.16, XR Interaction toolkit preview version 0.10.0, Oculus XR Plugin version 1.3.4, were used to add controller settings, main camera layout as well as to manage interactable UI.
- **Other assets**: Debris Toon Visual Effects Texture was used to develop debris falling from a height [25], another asset named Industrial Small Truck was used to carry concrete pipes [14]; an asset called Small Town America was used to build basic streets for the game scene [27], effect textures and prefabs were used to give special effects like explosions, smoke, sparks, and shockwave [8].

2.2.6 Exporting Prefabs from SketchUp

A few components for the construction site scene were created in SketchUp and exported as fbx files to Unity. For instance, SketchUp models of a tower crane, concrete pipes, wooden cable barrels, site fence, onsite temporary office, electrical powerline, and construction workers were imported.

2.2.7 Using Audio Assets

A developer requires an appropriate audio file to create audio effects in the game. Although there are many free audio files available on the internet, high-quality audio files are only available for purchase. The developer adds the audio file as a game object component to a particular prefab. The developer can modify the audio using the doppler effect, fade effect, and manipulate the controls to get the desired output. Adding the audio to a scene will make the game more immersive. The authors used freely available audio files in the game development.

2.2.8 Creating an Animated Object

There are multiple methods to animate an object in the game. For example, the waypoint system or artificial intelligence scripts or using basic frame-by-frame animations. Since the researchers had limited programming experience, they used the frame-by-frame animation method to create a looping animation. While creating animation, the authors experienced an error that crashed the Unity editor. The error stated, "Animation Event has no function name specified." The authors proposed a solution to this error. In the animation window where the Dopesheet and curves section is located, keyframes were added in the timeline. An animation event needed to be removed to ensure a continuous loop and smooth functioning of the game.

2.2.9 Creating an Interactable UI

The authors developed an interactive quiz in the virtual environment for this study. Users could interact by answering multiple-choice questions. The canvas and question text was created using the XR Unity packages. A video tutorial illustrated the process of building the UI [30].

2.3 Advantages of In-House Development

There are several outlets for purchasing off-the-shelf serious games developed for a wide range of training purposes. However, since every organization's needs are different, such games cannot meet the specific training needs. As a result, in-house proof-of-concept level productions allow for the testing of innovative teaching and learning methods before deciding on developing a complete training program. A few key benefits are given below.

2.3.1 Company-Specific Content

The in-house development process allows the developer to generate company-specific content.

2.3.2 Cost-Effectiveness

IVR-based serious games, when built by tech companies, are costly even though there is no guarantee that they will work.

2.3.3 Customizable Content

The in-house development process permits changes based on user responses and changing business needs at any time.

2.4 Discussions

The authors faced challenges while developing the game. New IVR game developers can overcome these challenges by following the lessons learned presented in the paper. Learning and implementing a game design system was challenging. However, the availability of training modules and tutorials proved helpful. Implementing the knowledge gained still takes time. Some limitations were related to interoperability.

For example, when detailed Building Information Models (BIM) are exported as an fbx file, they are incomplete. The materials present in the original file may not appear in the Unity game engine. In addition, the import–export processes sometimes crash the Unity engine.

The authors experienced that Unity software does not support various Unity versions, so they used only one version during the entire development process. Rendering and testing the game is a computing-intensive process, and it can lead to a system crash.

To create a successful animation design, the developer should resolve errors introduced due to the infinite loop system. One example of such error is "Animation Event has no function name specified."

To create a quiz in IVR, developers need to understand the game engine's advanced functions, including scripting and displaying quiz content.

3 Conclusions

This study was aimed to guide construction safety educators and those interested in using Virtual Reality for educational purposes on how to develop IVR-based serious games. Aside from basic knowledge of pedagogies and subject matter, the creation of Immersive Virtual Reality (IVR) learning games requires skills in using game engines, designing game assets, and coding in programming languages. Typically, game production is a collaborative endeavor. However, small businesses may not be able to afford to employ a team of experts to create proof-of-concept learning IVR games. That is why the authors created guidelines to help non-programmers develop IVR games in-house to gather evidence of their effectiveness. The lessons learned in this study will assist them in creating an effective strategy for developing IVR content by avoiding the pitfalls following the IVR content development roadmap identified in this study. As a result, they would be able to build the game more efficiently by bypassing the lengthy process of locating appropriate resources for game creation. If organizations are interested, they may use the data to determine whether to invest financial capital in developing a high-end IVR game. However, previous research studies have shown that not all IVR games are helpful. The authors discovered numerous learning tools available for game engines and computer languages, most of which are free. However, learning time varies according to the learner's prior experience and level of commitment.

Additionally, a developer should balance cost and time by deciding whether to use free or paid game assets. Although free assets reduce development costs, they can take longer to build. Therefore, by acquiring ready-to-use assets, production time can be shortened. Nonetheless, depending on the game's requirements, efforts are required to modify assets and prefabs. In general, it is hard to find tutorials that are specifically tailored to the needs of each game. That is why one must be open to adapting and applying what one has learned.

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Design and Implementation of a Fuzzy Expert System for an Ergonomic Performance Assessment in Modular Construction Operations Using the DMAIC Approach

A. Govindan and X. Li

1 Introduction

The workstation design, which does not take ergonomics into account, often involves awkward body positions for workers, which can contribute to musculoskeletal disorders or injuries. To increase comfort for staff, these stations need to be revamped using ergonomic analysis. In cases where the principles of ergonomics have not been considered in manufacturing plants, there is a need to improve or modify the workstations and the working conditions, which can increase worker comfort and potentially increase productivity for the entire manufacturing plant [18]. At the occupational level, ergonomics study sought critical causes of work-related musculoskeletal disorders (WMSD) such as static work, repetitive operation, exposure to vibration, abnormal posture, over usage of strength, lack of recovery, and monotony of task [26]. Brauner et al. [2] identified work duration as a crucial factor that determines the exposure of employees to physical stress and the availability of their recovery [2]. Researchers have brought about advancements in this domain by introducing ergonomic intervention in lean design, risk assessment tools, questionnaires for assessing physical load [11, 13, 20] etc. to make ergonomic improvements. Ergonomic improvements are usually made in industries considering the principles of occupational ergonomics, where the work environment is designed to match workers capabilities. Ergonomics can bring good results; help improve efficiency and decrease construction time and costs. Construction workers face high ergonomic risks that negatively affect the well-being and productivity of

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the workers. Therefore, it is crucial to accurately assess the workforce's ergonomic risk [4]. Ergonomists contribute to designing and evaluating systems to make them compatible with people's needs, skills, and limitations. Tee et al. [28] discuss the importance of assessing the potential ergonomic risk factors in the workplace using risk assessment tools like Rapid Upper Limb Assessment (RULA) and Rapid Entire Body Assessment (REBA) [28]. Ergonomic performance assessments are continuous, on-going processes that include the entire workforce present at the organization. Numerous organizations do not have adequate knowledge to execute their self-assessment process for evaluating organizational performance. They also indicate that the development of analysis tools for assessing industrial performance is very scarce [16]. Analyzing a business's performance is not a common practice, and proficiency in this area is obtained from practical experiences rather than formal education. Most managers overlook the advantages of performance analysis. They do not conduct them promptly due to the lack of staff availability and the time consumption that is involved, and thus, valuable information required for improving the organizational performance is lost [1]. Thus, there is a need to utilise a systematic and automated process within industries to minimize time and efforts to conduct ergonomic assessments and make decisions. This can be performed using the FES. Expert systems are a particular type of Decision Support System (DSS) that are a problem-solving software that performs well in a specialized problem field that is considered difficult and requires specialized knowledge and skills. A decision support system based on fuzzy logic can mimic human decisions based on the inputs provided [30]. The design and implementation of a fuzzy logic-based DSS, often called a FES, for ergonomic performance assessment, is expected to cut down the time it takes to identify the required changes in the workplace to make it more ergonomically safely. The FES can then help the ergonomists or managers focus most of their time in executing administrative or engineering controls based on the types of ergonomic hazards identified. This paper explores the effectiveness of utilizing a proposed FES to support the decision-making process to implement changes in the industry. It is done by eliminating or mitigating the ergonomic risk factors and supporting ergonomic performance benchmarking through ergonomic risk identification.

2 Literature Review

This section explores supporting literature that discusses the need to develop an FES for ergonomic assessments and how this form of artificial intelligence is being used in recent research. A brief review of why the DMAIC methodology will help develop the FES has also been included in this section.

2.1 DMAIC Framework

DMAIC refers to a cycle of data-driven enhancement used for business processes and designs to be improved, optimized, and stabilized. The primary method used to push Six Sigma ventures is the DMAIC enhancement loop. DMAIC stage model is not limited to Six Sigma and can be used as the basis for other applications for improvement by acting as a problem structuring device [5]. This problem structuring tool was used for development and application of the FES in this study. DMAIC is preferred for this study as it is a customer-focused, data-driven, and an organized problem-solving system that builds on learning from previous stages. In companies and projects where there is a need for continuously improved processes, this tool proves to be an appropriate and flexible framework to discover and execute best practices.

2.2 FES and Its Applications in Various Fields

Numerous expert systems consist of inference engines based on dual logic, whereas FES's are based on fuzzy logic and approximate reasoning [23]. The basic idea behind a FES is to use fuzzy logic rather than Boolean logic. When conventional statistical reasoning and other techniques to combine degrees of uncertainty are insufficient, we realize a need for a FES [3]. Fuzzy systems can store experts' knowledge in the form of rules or mathematical expressions that can be flexible to envision and adjust the system. The fuzzy system can be perfected to attain good performance by adjusting the membership functions and parameters by involving manual methods of trial and error since the fuzzy system's performance can be susceptible to the specific values of parameters [19]. A fuzzy logic system consists of four main subsystems: fuzzification, inference, rule base, and defuzzification [17]. Implementing intuition, heuristics, and expert knowledge in the domain are some of the main advantages of utilizing a FES. The key benefit of these systems is that the knowledge progressively helps attain expertise and can be used in crucial circumstances as a decision-making method that replaces traditional FAQs [25]. Thus, this system can help benefit ergonomic assessments in modular construction industries to conduct a rapid ergonomic assessment to support the ergonomic intervention plans. It is possible to supplement traditional statistical validation methods based on numerical data with human expertise, which often requires heuristic knowledge and intuition [32]. Fuzzy logic has been successfully used in several areas, such as control systems engineering, image processing, power engineering, industrial automation, robotics, consumer electronics, and optimization. This mathematics division brought a new life into scientific fields that have been stagnant for a long time [27].

Jabłoński and Grychowski [14] have designed a system that assesses indoor environmental conditions using data gathered by numerous sensors based on occupants' comfort. Pokorádi [24] have developed a fuzzy system that can make accurate risk assessments which can help make decisions in the real world to ensure safety. Falahati et al. [6] used the fuzzy logic approach to predict WMSD among automotive assembly workers based on self-reported questionnaires and REBA assessment using the MATLAB software. Golabchi et al. [9, 10] proposed a fuzzy logic approach using Rapid Upper Limb Assessment (RULA) scoring system modelled using fuzzy logic to prevent ergonomic injuries. Fayek and Oduba [7] illustrated how to develop a FES to predict industrial construction labour productivity given the realistic constraints of multiple contributing factors, subjective assessments, and limitations on data sets. Wang et al. [31] proposed a dedicated rule based-fuzzy system paired with an automated 3D ergonomic risk assessment tool to record the incremental transitions of continuous human motion without triggering sudden changes in risk scores. These papers use different tools and techniques to make an ergonomic risk assessment. Although, there has not been a study that demonstrates a method to display the overall ergonomic risk present in an industry that includes physical ergonomics, environmental ergonomics and, cognitive ergonomics at the same time. Generally, in the literature, ergonomic risks are assessed to better workplace conditions for WMSD, focusing on various ergonomic assessment tools, betterment of environmental conditions, and improvement of labor productivity, prevention of ergonomic injuries. In the industry, ergonomics is usually associated with occupational health and safety and related legislation rather than business performance. Ergonomic performance analysis in the perspective of business success is often ignored due to its cumbersome and time-consuming nature. Despite several studies focusing on various aspects of ergonomic risk assessments using DSS, there are no studies that focus on developing a DSS that helps decision-makers quickly make decisions in such a way that the DSS includes all aspects of ergonomics. This paper investigated the preliminary reliability and application of an FES to evaluate overall micro ergonomic performance to minimize ergonomic risks and injuries in the industry.

3 Proposed FES for Ergonomic Assessments

This section discusses the method and benefits of integrating a proposed FES with the DMAIC framework on speeding up the ergonomic assessments without frequent input demands from professional analysts. The contents, detailed development and implementation methodology of the FES will also be further discussed.

3.1 Methodology and Application of the FES using the DMAIC Framework

The novel FES developed in this paper uses DMAIC methodology as a problem structuring device. The proposed FES performs functions such as estimating the

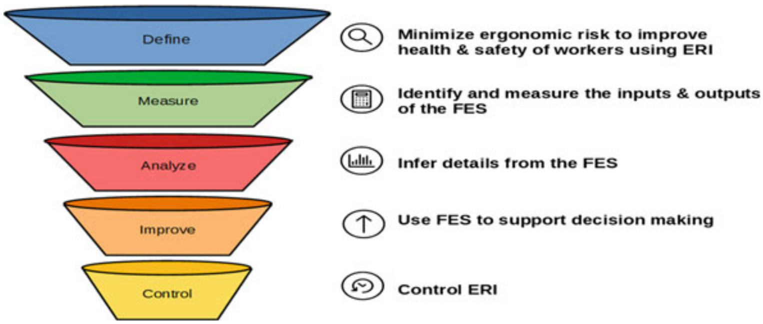

Fig. 1 Development and application of the FES using the DMAIC framework

ergonomic risk present in physical postures of workers, workplace environment, and sensory demands required for the workers to obtain the overall level of ergonomic risk present in the industry. This section discusses the details for the development and application of the FES in terms of DMAIC stages (Fig. 1).

Define—Selection of problem and identifying potential benefits: The selected problem and potential benefits are to minimize ergonomic risks to improve workers' health conditions and improve overall industrial productivity by proactively reducing/eliminating the potential ergonomic risks using the Ergonomic Risk Indicator (ERI) of the FES.

Measure—Measurement or quantification of the problem to determine the current performance of the process: Scientific studies show that risk factors such as awkward posture, force, repetition, static loading, contact stress, illumination, noise, extreme temperature, vibration contribute to ergonomic risks and impede workers and their work nature [8, 15]. The design of cognitive work is also an essential aspect of the human operator at work. Operators must not be overloaded with auditory and visual information [4]. Thus, there is a need to cluster types of ergonomic risks under suitable titles. The Physical Metric helps evaluate the whole-body postural WMSD based on the frequency of occurrence, forceful exertion, type of movement or action and, coupling. Environmental Conditions metric helps evaluate the interaction of workers with their physical environment. Sensory Demands Metric helps assess workers' sensory strains, based purely on physiological sensations that occur due to the design and comfort of the surrounding environment. The ERI, as the output of FES, can be used in the industry as a Key Performance Indicator (KPI) to numerically and linguistically indicate the intensity of overall ergonomic risk present in the industry. The ERI shows an increase or decrease in employee safety, comfort, and performance as per the combination of inputs provided. The FES architecture displayed in Fig. 2 indicates the various systems used as a part of FES. The data required for determining the identified metrics will be explored further in detail in Sect. 3.1 and 3.2. Data for the targeted metrics was collected from the industry using observation-based data collection, interview, measurement and supporting industrial documents such as the Physical Demand Analysis (PDA) form and Standard Operating Procedure (SOP).

Analyze—Identification of factors that influence the problem: The nature of the FES is such that it allows us to infer details from the inputs provided and outputs obtained. The FES can be used either in the absence or presence of an expert due to its rule base and help in the process of analysing and effective decision making for making improvements. The FES can be considered as an efficient substitute for the generally used DMAIC tools such as Cause and Effect diagram, Process Map Analysis and Subprocess Mapping for the selected problem statement.

Improve—Design and implementation of a new process to improve performance by eliminating or mitigating the influential factors that caused the problem: This phase of the DMAIC cycle cannot be directly supported by the developed FES but it helps support the decision-making process that can contribute to implementing changes in the industry by eliminating or mitigating the ergonomic risk factors.

Control—Control of the improved process and future process performance: The ERI can be used for internal ergonomic performance benchmarking. This KPI can be used to help practitioners in the process of continuous improvement through monitoring ERI and controlling the ergonomic risks by utilising the FES at regular frequencies.

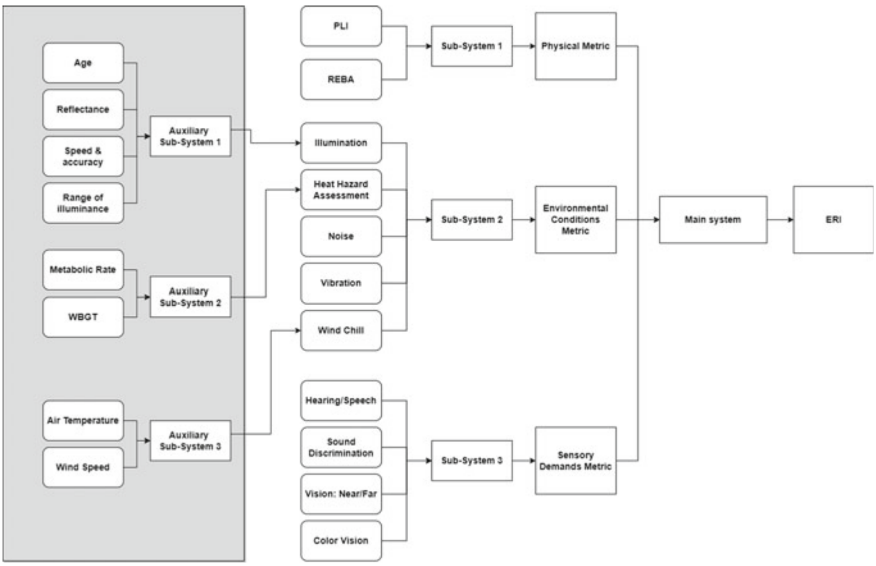

Fig. 2 Architecture of FES

3.2 Development of Sub-Systems and Auxiliary Systems to Support the Main System

The proposed FES was created using the interface provided by the fuzzy logic toolbox that is available in MATLAB. The fuzzy logic toolbox allows the users to customize the linguistic variables and membership functions of the corresponding fuzzy inputs and outputs as per the fuzzy rule base's design. The Mamdani-type inference system is implemented for this purpose in the study. The architecture for the proposed FES is demonstrated in Fig. 2.

The FES was categorized into three separate subsystems 1, 2, 3. In subsystem 1), the input parameters were Physical Load Index (PLI) and Rapid Entire Body Assessment (REBA). The output parameter in this subsystem 1 was physical metric. The reason behind adopting the mentioned input and output parameters was to assess the level of physical, ergonomic risk present in the industry's workstations. The input parameters for this subsystem were adopted from ergonomic assessment tools developed by Hol et al. [13] and McAtamney and Hignett [20]. PLI is a tool for assessing the physical workload based on the frequency of the postures used, which is created by integrating information from a biomechanical model of the lumbar load. REBA assessment can help analyse the musculoskeletal risks in various tasks since it is a sensitive postural analysis system. REBA offers scores for muscle activity caused by static, dynamic, rapidly changing, or unstable postures. The rationale behind using two physical, ergonomic assessment tools was to accurately assess the level of risk present by exploiting the combined advantages of both tools. REBA assessment is primarily based on postural analysis, while PLI assessment is mainly based on the frequency of postures used.

The second subsystem contains the following input parameters: Illumination, heat hazard assessment, noise, hand-arm vibration, and wind chill. This system has the Environmental conditions metric as its output parameter. These parameters were selected as they are the most crucial parameters determining the risk levels present in the workplace environment and most relevant for modular construction industries. The input parameters illumination, noise, and wind chill of this subsystem were based on 'recommended illumination levels for use in interior lighting design', 'permissible noise exposure' and 'equivalent wind chill temperature of cold environments under calm conditions' charts adapted from various sources as suggested by Freivalds et al. [8] The input parameter, heat hazard assessment, was developed based on Heat Stress standards recommended by Occupational Safety and Health Administration [22]. The input parameter, Hand-arm vibration, was based on HSE's recommendation limits [12].

Input parameters such as illumination, heat hazard assessment, and wind chill have their own set of input parameters which are a part of their auxiliary subsystems. The input parameters taken into consideration for building the illumination auxiliary subsystem (auxiliary subsystem 1) were the age of workers, the reflectance of task/surface background, speed and accuracy required, and range of illuminance [8]. The input parameters that were used for building heat hazard assessment auxiliary subsystem (auxiliary subsystem 2) were the metabolic rate of workers and Wet Bulb Globe Temperature (WBGT) [22]. The auxiliary subsystem of wind chill (auxiliary subsystem 3) had input parameters: air temperature and wind speed [8].

In terms of subsystem 3, the input parameters selected were based on the frequency of sensory demands used in workstations such as Hearing/Speech, Sound discrimination, Vision: near/far, and Color vision. The sensory demands were recorded based on the list of frequency categories (1) Never (0%); (2) Rare (1–5%); (3) Occasional (6–33%); (4) Frequent (34–66%); (5) Continuous (67–100%). The input parameters were categorized and recorded subjectively by the observer. The output parameter of this subsystem is called Sensory Demands Metric and was developed based on work of Sensory demands factors proposed by Li et al. [18].

These three subsystems were created using fuzzy logic rules, which were generated using heuristic techniques. This FES can also handle inaccurate or vague data that might be translated for decision-making since fuzzy systems resemble human reasoning, to solve complex problems.

3.3 Development of the Main System

The main system was constructed using physical metric, environmental conditions metric, and sensory demands metric as input parameters. The output parameter obtained in the main system is called an ERI. Nonetheless, it is essential to note that the main system's input parameters were attained from the outputs of subsystems 1, 2 and 3. The FES is responsible for determining the output values based on targeted variables or input parameters, which are based on a set of if–then rules. The mapping of input values to output values acts as a foundation that aids in decision-making. The auxiliary systems, subsystems and main system were created by the selection of fuzzy inputs and outputs, selection of linguistic variables and their corresponding membership functions for the fuzzy inputs and outputs and finally mapping the fuzzy inputs with the fuzzy outputs. The FES was created based on the collective knowledge obtained from physical assessment tools, charts, guidelines and standards. Effective use of ERI includes a detailed understanding of the insights provided in the subsystems as they will assist the industries in identifying the areas in which changes are needed. The membership function of the physical metric was defined using linguistic variables such as Low Risk (LR), Medium Risk (MR), High Risk (HR), and Extremely High Risk (EHR) whereas, the environmental metric and sensory demands metric used linguistic variables such as LR, MR and HR. The membership function of the ERI was defined using linguistic variables such as LR and HR to indicate the overall ergonomic risk present in the industry. The main system was developed by using 36 heuristic rules. For example, if Physical Metric is HR, the Environmental conditions metric is MR, and Sensory Demands Metric is HR, then ERI is HR. Similarly, for different combinations of the input parameters, the plausible ERI was projected in the rule base.

4 System Application and Preliminary Reliability Study

The developed FES system was tested for a modular construction industry to minimize ergonomic risk for the **Define** phase of the DMAIC process. The main system's input parameters (1) Physical metric; (2) Environmental conditions metric, and (3) Sensory demands metric was obtained from the industry data that was collected for all the input parameters to complete the **Measure** phase. The FES generated a value of 0.0326, 0.426, and 0.5 for the physical metric, environmental conditions metric and sensory demands metric. A value of 0.085 was generated for the output parameter ERI. To extract further insights from the FES, the membership functions of the input and output parameters will have to be **Analysed**, and this can be done by exploring the input and output parameters of the subsystems. To properly understand the insights from this study, there is a need to understand the relationship between the main system's input factors. The three input factors of the main system are inter-related to a certain extent and may either positively and negatively affect one another's behaviour and the ERI. For example, an improvement in the environmental conditions can bring forth a positive change on both the physical metric and the sensory demands metric. The proposed FES explores the effect of the different combinations of the three input parameters can have, on the ERI. In this case study, the modular construction industry selected predominantly shows a medium risk in all three input parameters. However, in cases where the input parameters have different degrees of risk, the input parameter that displays the highest degree of risk should be treated and **Improved** first as it will contribute to the majority of the ergonomic risks. The true strength of DMAIC lies in the **Control** phase, where ERI can be used for benchmarking, which helps identify internal opportunities for improvement in the future.

4.1 Relationship Between Ergonomics and Safety Hazards

Due to humans, equipment, materials, environment, and operation, health and safety hazards may occur. Besides, injuries and accident incidences are always not the results of a single occurrence. Multiple variables lead to certain unfortunate incidents. In the sense of occupational safety, when the concepts of ergonomics are applied, the idea of ergonomic safety emerges. Being cautious of the ergonomic and safety hazards in an industry guarantees that the equipment, materials used by a worker, the working environment, and operations performed by the worker are suitable to meet the worker's job requirements and personal capabilities. Thus, there is a need to check the developed FES's feasibility and be compared with an existing benchmarking standard for safety hazards.

4.2 Comparison of OSHA Incident Rate and ERI

An OSHA Incident Rate is a measure of how frequently a reportable accident or illness occurs over a given period, typically one year, in any industry. Incident rates are a very effective indicator tool that serves as a benchmark for assessing the safety program in any industry and can be used to compare relative level of injuries and illnesses between different sectors, companies, or activities within a single company with fairness, no matter the size of the workforce in the industry [21]. To check the feasibility of the developed model, OSHA Incident Rate and ERI results will be displayed in Table 1. The results will also be compared and analysed. The formula to calculate the OSHA incident rate is provided below.

$$\text{OSHA Incident Rate} = \text{N}/\text{EH} \times 200{,}000 \tag{1}$$

where,

N is the No. of Recordable Injuries and/or Illnesses in one year;

EH is the Total no. of hours worked by all employees in one year;

EH = 252 workdays/year × 8-h shift × 130 employers.

Both OSHA incident rate and ERI were lagging indicators and were expected to have a strong correlation between them before the results were obtained for each indicator. This assumption was made due to the overlapping factors such as humans, equipment, materials, environment, and operation that cause safety hazards and ergonomic hazards. OSHA incident rate of the industry is considered to be safe if it lies below the national average. In 2019, the prefabricated wood building manufacturing industry (NAICS-321992) had an average of 13.80 [29]. The industry partner's OSHA incident rate who belongs to the same sector taken for this case study, obtained an incident rate of 6.87, which is much lower than the national average and is thus considered safe. The ERI developed in the FES is measured on a scale of 0–1. The ERI score based on collected data for the input factors was 0.085 and lay predominantly in the Low Risk (LR) region. We can infer that the ergonomic and safety risks are considerably low for the results obtained from both these indicators, as expected.

Table 1 Comparing the results of OSHA incident rate and ERI of the case study

Year	No. of recordable injuries and/or illnesses in one year	Total no. of hours worked by all employees in one year (h)	OSHA incident rate	Prefabricated wood building manufacturing industry average NAICS-321992	ERI
2019	9	262080	6.87	13.80	0.085

4.3 Limitations and Further Steps for Validation

The developed FES needs to be validated further by comparing its effectiveness in various circumstances and this can be accomplished by comparing and analysing ERI performance based on OSHA incident rate results between various organizations within the NAICS-321992 category; or by comparing the results of the same organization for different years or quarters. The FES's effectiveness also needs to be tested for various seasons since modular construction industries in Canada generally tend to have more workload in summer and lesser workload in winter. If in-depth assessments are to be conducted with the same FES model for each workstation, then the FES's efficiency needs to be tested and validated for individual workstations present in the same organization or various organizations within the NAICS-321992 category as well.

5 Discussion and Conclusion

The development of the FES for ergonomic performance assessment of modular construction operations has been described in this study. This study has presented a novel system for evaluating the overall ergonomic risk present in the industry based on a physical, environmental and cognitive basis. This system is meant to aid ergonomic analysts and managers in understanding the overall ergonomic risk present in the industry with the ERI. Moreover, industries can also use this system to obtain their insights from the ergonomic risk factors within the subsystems which further eases the decision-making. It also helps ergonomists and managers focus the majority of the time in executing administrative or engineering controls based on the types of ergonomic hazards that have been identified as this is the only value-added ergonomic time that can directly contribute to increases in productivity through the betterment of the health and safety of workers. Industries can utilise the power of continuous improvement by using the FES and it can also help establish a growth mindset amongst employees. The proposed FES can support significant efficiency gains and improve working conditions simultaneously. Improving workplace ergonomics may contribute to increased productivity if the industry was not already performing at optimal productivity levels. Additionally, claims and injuries can be reduced, and the worker compensation costs can also be reduced by keeping ergonomic risks under control. In a practical sense, this FES can be used to as a tool for conducting quick ergonomic performance audits for the organization. An additional advantage is that, it is much faster than other methods of ergonomic analysis, and it can be used by ergonomists, managers, other experts, and even staff themselves. Deployment of this FES can shorten decision making cycle, reduce cost of decision making, help make unbiased decisions even without technical knowledge in the field of ergonomics.

6 Future Directions

The presented FES can be altered to suit the evaluation of ergonomic assessment for any industry by tweaking the system's contents. The implementation of the proposed FES is required to be validated in detail for the modular construction industry. The proposed system relies on observatory data collection and this can be time-consuming and error-prone, and thus there is a need to improve the method of data collection. The current system does not support real-time data capture of employees' working conditions in the industry for the FES. Nevertheless, it is possible to collect real-time motion capture data and real-time environmental data using sensors. If data can be collected and integrated in real-time, further improvements can be made to the proposed FES. Real-time data analysis can play a significant role in decision making, especially for eliminating non-value-added time. Furthermore, the DMAIC cycle's improvement phase can utilise Virtual Reality and Augmented Reality technologies to quickly estimate if the suggested ergonomic interventions improve the worker's environment, comfort, and safety without having to deal with implementation costs.

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Using Data Mining for Prioritizing Roof Rehabilitation Works

Kareem Mostafa and Tarek Hegazy

1 Introduction

Assessing the condition of existing assets serves as the background data repository based on which all asset rehabilitation decisions are made. For large owners that own many buildings, such as school boards, however, collecting inspection data for buildings is a major undertaking that is costly and time consuming. Currently, most inspections to determine the conditions of assets are done manually and result in hand-written reports showing the inspector's personal judgement of the criticality of the components under inspection. These reports, in addition to being subjective, lack the granularity needed to do the fund allocation properly [1]. The low resolution of inspection data leaves many roofs being classified at critical condition. This makes the allocation of the limited rehabilitation funds a very challenging task. It is up to the facility manager to further classify the rehabilitation events to abide by the limited budget available. There is a need, therefore, for a data-driven approach that allow better fund-allocation decisions, which is referred to as a "Moneyball" approach. By mining and leveraging player performance data, Oakland A's manager Billy Beane challenged conventional wisdom of scouts to outsmart richer clubs, creating a top baseball team on a limited budget [2].

Data analysis to support inspection and maintenance of buildings has interested many researchers over the years. Ahluwalia and Hegazy [1] classified roofing photos into categories and used it as visual guidance during inspection. Hegazy and Gad [3] used two years of reactive maintenance data from 88 schools in Canada to predict the condition of major building systems without inspection, and identify the systems that have conflicts data, to prioritize them for inspection. More recently, advancements in information technology and data mining have allowed ways to better explore existing

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datasets and discover trends and patterns that can aid the decision-making process. Data mining techniques have been extensively used to enhance the inspection of buildings and other infrastructure systems. Gunay et al. [4] and Mo et al. [5], for example, analyzed building work orders and maintenance requests to detect failure patterns and help assign the needed maintenance crews. Similar work was done on bridge inspection reports by Liu and El-Gohary [6] to extract defect type and severity information.

Using real inspection data of roofing systems, this study uses data mining and clustering techniques to offer a more granular classification of roofing criticality. The study utilizes WEKA [7], a powerful open-source tool that includes multiple supervised and unsupervised learning methods, and compares the results of various clustering techniques. Based on the analysis, top priority roofs for rehabilitation have been identified. The study helps owners of large asset portfolios (e.g., municipalities and school boards) optimize the reliability and performance of their assets while abiding by their budgetary constraints.

2 Dataset

The Toronto District School Board is the largest school board in Canada. TDSB owns more than 600 schools and administrative buildings across the Toronto Metropolitan area. To maintain the service level of the different buildings while abiding by the different budgetary and temporal constraints (e.g., repair works need to be done during the summer break period). TDSB has created a predefined building hierarchy (shown in Fig. 1) to streamline the inspection and asset management processes. This building hierarchy divides the buildings into systems (e.g., structural, mechanical, architectural, etc.), then subsystems (e.g., superstructures, foundations, interior and exterior walls, etc.), and finally into components. Information about each component's life span and possible defects are stored in TDSB databases. Once

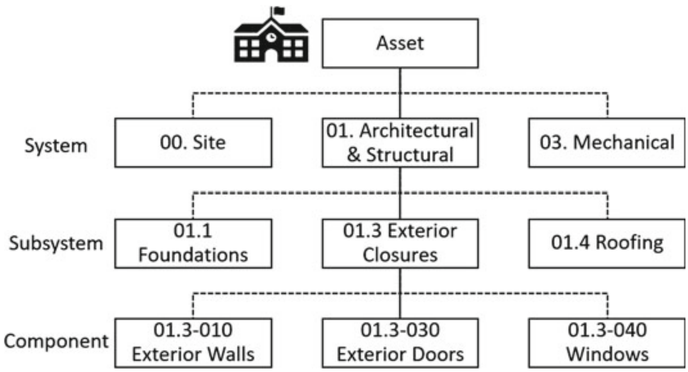

Fig. 1 TDSB building hierarchy

every five years, the schools are inspected by professional consultants who provide a report showing the buildings' condition and suggesting an appropriate rehabilitation strategy if needed.

This study uses inspection reports of 400 different schools with a focus on the Roofing subsystem. Information about the suggested rehabilitation actions (called events in the inspection reports) were extracted using a VBA macro code. After an initial analysis of the collected inspection reports, the final dataset used includes the following attributes about each roofing system:

1. **Event Type**: Repair or Total-Replacement;
2. **Age**: The difference between the year when the rehabilitation event is suggested to take place and the school's construction year, unless indicated otherwise in the event description;
3. **Event priority**: The inspector's assessment of the event's urgency; High, Medium, or Low; and
4. **Total Count**: A field created in the initial analysis that translates the text description of the rehabilitation event into numerical data of the number of occurrences of defect-related keywords (e.g., leakage, broken, etc.). It is assumed that the higher the number of occurrences of the defect-related keywords, the higher the damage extent.

3 Clustering Algorithms

Clustering is an unsupervised machine learning technique that aims to classify the data to "clusters" of similar attributes [8]. Because of its ability to explain underlying data structure and highlight significant features, as well as help with decision making by organizing the data into understandable groups [9], clustering techniques have been adopted by researchers in multiple domains. Examples include construction safety [10], marketing [11], medicine [12], and others. A brief description of the three clustering methods used in this study is provided in the following subsections.

3.1 Canopy Clustering

Canopy clustering is a simple, fast, yet highly accurate clustering method [13]. The first stage uses fast proximity measurement methods to divide the data into overlapping subsets (i.e., canopies) based on distance thresholds (T1 > T2, set manually or through optimization) as shown in Fig. 2 [14]. For each point, the distance between the point and the centers of clusters are examined. If the distance is too large (larger than T1), then the point is considered to be the center of a new cluster), but if the distance is too small (smaller than T2) then the point is removed from the set [14]. This way points that are too close to one another are removed which reduces the computational

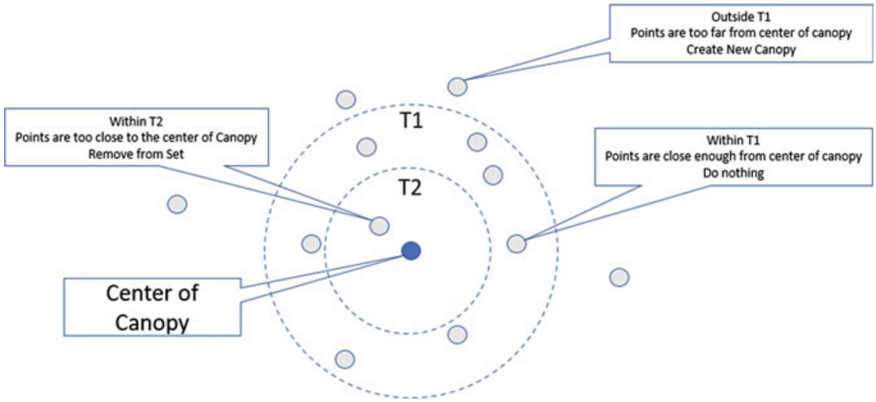

Fig. 2 Canopy formation

burden required for the second, and more sophisticated, stage: centroid calculation [14].

3.2 K-Means Algorithm

K-means is a well-known algorithm that aims to group objects into a predefined number of clusters (k) such that the within-cluster sum of squares is minimized [15]. First, k points are randomly chosen to serve as the initial centroids for the clusters, and all other points are then assigned to the centroid they are closest to. After that, for each cluster a new centroid is computed [15]. Based on the new centroids, the datapoints are reassigned to the clusters and then new centroids are calculated. This assign-calculate-reassign cycle is repeated until convergence.

3.3 Farthest First (FF) Clustering

The (FF) technique shares the cluster assignment and centroid selection concepts with the K-Means algorithm discussed earlier, FF chooses the point "farthest away from other cluster centers" as the new cluster center [16]. This means that FF algorithm is faster because it only requires a single pass. Also, cluster centroids produced by the FF algorithm correspond to real points [17].

4 Results and Findings

Since the different clustering techniques differ in the way they attempt clustering, it is expected that their results would have some variations. To simplify the visualization of results, the *Event type* and *Event priority* categories were combined under one parameter referred to as *T&P*. For example, an event that has *Event type* = *Replace* and *Event priority* = *High* will have a T&P value of *Replace/High.* The results obtained from using the canopy and FF clustering algorithms have shown to be relatively similar, as presented in Figs. 3 and 4, respectively. Figures 3a and 4a represent the clustering results based on the *Total Count* and *Event Age* information, with the shape of the datapoint representing the type and priority of the event. For a better visualization, the T&P visualization can be viewed separately in Figs. 3b and 4b.

As seen in Figs. 3b and 4b, both the Canopy and FF algorithm have reached the same results in terms of creating the first two clusters. Both algorithms have elected to store all the Medium priority events in Cluster1, and all the Major Repair events in Cluster2, leaving Clusters 3 and 4 for high-priority-replacement events. The difference between the two methods can be seen in the threshold created to assign

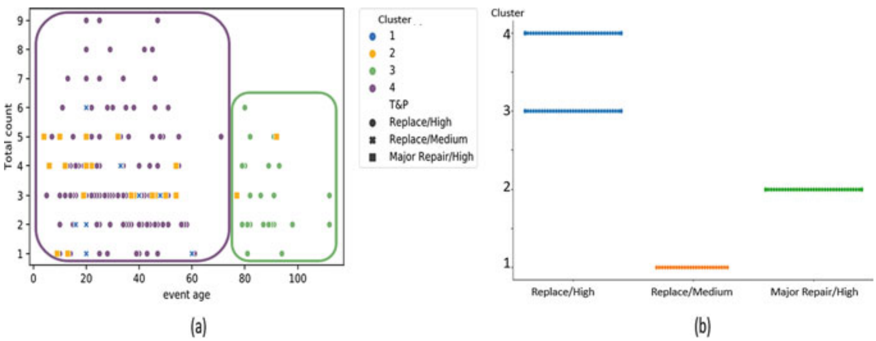

Fig. 3 Clustering using canopy

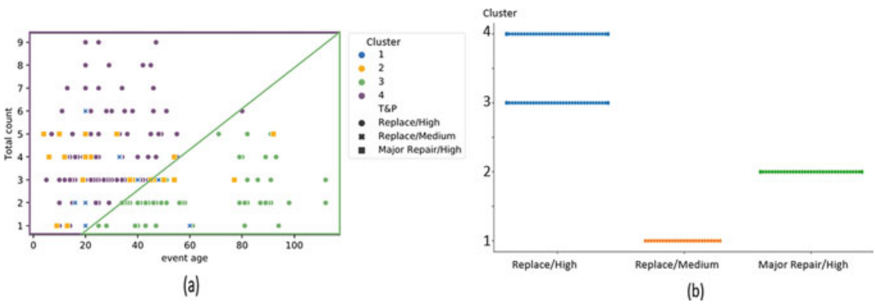

Fig. 4 Clustering using farthest first (FF)

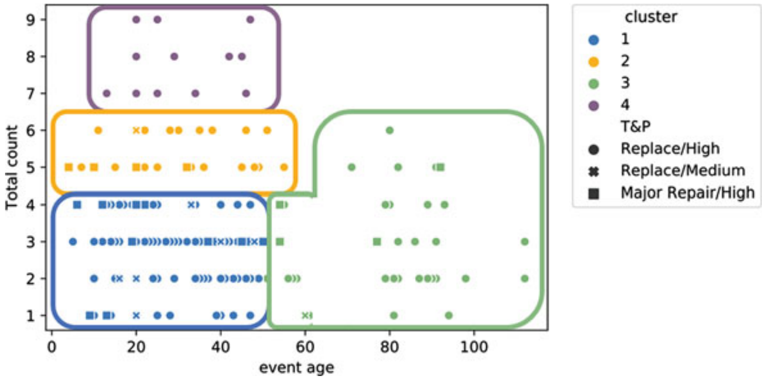

Fig. 5 Clustering results based on K-means algorithm

datapoints to clusters 3 and 4. This can be seen more clearly in Figs. 3a and 4a. The threshold created by the canopy algorithm is at *Event age* = *70*, assigning all events whose age is higher than 70 to cluster 3 and all events whose age is lower than 70 to cluster 4, regardless of the severity of the defects (i.e., the *Total Count*). The Threshold created by the FF algorithm, on the other hand, is different and combines both the *Total Count* and the *event age* parameters. An event is assigned to cluster3 if *Total count* < *Event age/20,* and is assigned to cluster4 otherwise. The results using the K-Means algorithm are shown in Fig. 5.

It can be seen from the K-Means results in Fig. 5 that the algorithm has performed all its clustering based on the *Event age* and *Total count* attributes only. The clustering rules deduced from the Fig. 5 seem to be straight forward and allocates little weight to *Event type* and *Event priority*. Simply, if *Event age* is higher than 50, then the event is in cluster3. Also, cluster1 includes all events whose *Total count* is less than 4; cluster2 includes all events whose *Total count* is higher than 4 but less than 7 (i.e., *Total count* = *5 or 6*); and cluster4 includes events whose *Total count* is higher than 6. Unfortunately, there were no data points that represent old buildings (*Age* > 60) with high defect word count (*Total Count* > 6). As such, for application purposes, it will be assumed that this category of buildings shall belong to cluster 4 (i.e., highest criticality).

5 Discussion

A comparison among the three clustering algorithms in terms of the percentage of events assigned to each cluster is shown in Table 1. It can be seen that K-Means algorithm is the only algorithm that assigned a low number of events (13% only) to cluster 4, the cluster corresponding to the highest priority. It can be seen from Figs. 3, 4 and 5 above that the same events assigned by the K-Means to be of highest priority

Table 1 No. of events in each cluster for different clustering methods

	Canopy (%)	FF (%)	K-Means (%)
Cluster1	2	2	53
Cluster2	4	4	24
Cluster3	6	20	10
Cluster4	88	74	13

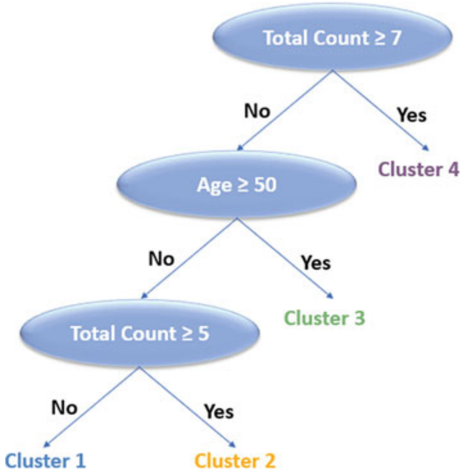

Fig. 6 Decision tree developed based on K-means clustering results

have been assigned the same priority level by the other algorithms. Therefore, K-Means is deemed to be the algorithm most helpful to decision making personnel to best allocate a small rehabilitation budget. Based on the structure of the clusters created by the K-Means algorithm, a simple decision tree is developed as shown in Fig. 6.

6 Conclusion

This paper presented the results of utilizing data mining techniques to provide a more granular prioritization scheme for asset criticality. This would help asset management professionals make the best use of their budgets to prolong the service life of their asset portfolio. The paper examines three clustering techniques to determine their effectiveness towards classifying roofing rehabilitation events according to attributes such as age and damage extent. The results show that the K-Means algorithm only assigns 13% of the events to the cluster of highest priority. This means that K-Means clustering is the method most helpful to asset management professionals operating with tight budgetary constraints. As such, a decision tree based on the K-Means Clustering results have been developed. Future work includes incorporating more data from different sources such as images, apply the same concept to analyze the rehabilitation events of different building elements to develop a comprehensive building assessment, and develop an optimization framework that considers budget limitations and multi-year asset portfolio investments.

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Evaluation of the Return on Investment of BIM—The Case of an Architectural Firm

N. Lechhab, I. Iordanova, and D. Forgues

1 Introduction

The Companies are always on the lookout for ways to improve their efficiency and productivity to satisfy their increasingly demanding customers. To this end, they use new practices such as Building Information Modeling (BIM), which is required by major clients such as the Société Québécoise des infrastructures (SQI). The structured use of BIM consists of developing new bases for collaboration between all project partners by adopting concerted approaches and using technology to achieve better projects and by delivering better quality projects [1]. The implementation of BIM in a company must be done according to an adapted, progressive, and thoughtful strategy to achieve a business plan. It is important to first analyze the working method implemented by the company to properly define the steps to be taken, to adapt this method to the BIM process. This strategy must define the objectives, desired results, means, and risks associated with the BIM adoption process, as well as measure the return on investment (ROI) of BIM [2]. The adoption of BIM requires significant and ongoing investment in hardware, software, training, and processes to achieve its potential value, making ROI calculation a critical evaluation step before any investment, as it allows the economic impact associated with the process change to be assessed. However, there is no standard method for calculating the ROI of BIM in the construction industry, despite the interest and confidence it generates when making BIM investment decisions [3].

Many companies that have embarked on the BIM adventure are unable to calculate ROI [4]. This is likely due to the lack of predefined performance indicators (KPIs) in the BIM implementation strategy, the fragmented nature of the construction industry, the fact that each project is unique, and the difficulty in quantifying intangible benefits

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of BIM, such as customer satisfaction [2]. Within this framework, the issue around which this project is structured is to define and measure the ROI for the implementation of BIM. The question that arises is: What would be the method to be used to measure ROI, and what are the performance indicators to be taken into consideration? To meet this challenge, an action-research approach involving an industrial partner is put in place to evaluate the viability of BIM deployment in the firm. This is the case of «ABC», an architecture firm that has designed several projects using BIM tools (Revit). The main objective of this action-research is to define and validate a method to empirically measure the ROI of BIM implementation, based on relevant literature that constitutes the theoretical framework of the study. Thus, the following specific objectives are aimed at: Identify the benefits of BIM at the project and enterprise level, as well as the return on investment of BIM implementations; Review the ROI calculation methods proposed by other studies; Develop a framework for measuring the ROI of BIM implementations at the architectural firm.

There are very few methods and examples of ROI calculations related to design processes [5]. The project set up is therefore intended to be an exploratory study. For this purpose, a case study within the architecture firm ABC is necessary to identify similar projects, carried out in BIM (with and without Revit template) and in conventional mode, to build a database gathering information on completion deadlines and costs, as well as tangible and intangible factors that will be used to establish comparative analyses to measure the return on investment. Tangible factors include cost reduction and faster project delivery. The intangible factors of BIM contribute to a reduction in the number of requests for information, as well as the number of unforeseen events, which is an advantage because there are fewer changes along the way that would result in higher costs and delay the progress of the project. These types of factors also contribute to improved marketing, customer satisfaction, the recruitment process, and staff retention, as well as to the offer of new contracts [6]. Finally, the results obtained after measuring the return on investment by evaluating the quantifiable benefits of BIM allow a decision to be made on the possible future implementation of BIM, or even its widespread use within the company. The work of this action-research may serve as a basis for developing a strategy to be implemented to allow the evaluation of the return on investment in construction innovation projects.

2 Literature Review

2.1 Identification of Key Performance Indicators (KPIs)

Representatives of the construction industry base their decisions to invest in BIM on the expected impact on the performance of the construction project. Therefore, an assessment of the quantitative and qualitative benefits of BIM is necessary [5]. Determining what needs to be measured and what should be measured at the construction project level is a major challenge to quantify changes and targeted benefits. More generally, construction projects are measured using key performance indicators (KPIs). However, these KPIs are often not consistent from one project to another, leading to confusion about: what should be measured, how it should be measured, what the sources of change are, and how to assess the success or failure of a project [1]. According to Cox et al. [7], KPIs are compilations of data measurements used to evaluate the performance of a construction operation or a particular task. Examples of qualitative KPIs suggested in the literature are safety, staff turnover, absenteeism, and motivation. In contrast, examples of quantitative KPIs suggested in the literature are units/man-hours, dollars/unit, cost, timeliness, resource management, quality control, percentage of completion, hours of work saved, time accounting, and scorecard [8, 9]. In addition, this study focuses on the decision to adopt BIM among architects and the factors involved in that decision. According to Coates et al. [10], the steps to follow for the identification of the KPI are:

- **Step 1**: Conduct brainstorming sessions within the company and interview external stakeholders with whom it collaborates,
- **Step 2**: Fill out a KPI design form for all potential KPIs collected during the brainstorming sessions and interviews with external partners,
- **Step 3**: Evaluation and assessment of potential Step 2 KPIs for filtering against the above checklist recommended by Gerber and Rice [11].

Abdirad's research [12], reports many studies (a total of 97 references are analyzed selected from 322 studies) to identify, extract and rank the metrics/KPIs used to assess BIM implementation. In this paper, the most important KPIs are those used to evaluate BIM tools, BIM users, the BIM process, BIM models, and BIM performance during the design phase. Although the criteria identified (e.g., collaboration, communication, interoperability, etc.) may not reflect any measures, the author intends to flag them to facilitate the development of quantifiable metrics or indicators for future research.

In summary, the KPIs identified for a construction project are presented in Tables 1 and 2 and are classified into two categories:

- Quantitative KPIs: cost, time, and labor productivity.
- Qualitative KPIs: staff maturity level, data access, understanding and information sharing.

2.2 *Methods for Evaluating the Performance of the BIM Implementation*

The development of BIM and the study of its ROI are inseparable from the outset. It is to be expected that, for a technological initiation to hold its own in a competitive business world, it must have a real economic basis [13]. Users who want to adopt BIM

Table 1 Summary of quantitative KPIs

Metrics	Quantitative KPIs	Unit
Costs	Unit cost of the project (design and construction)	$/m^2$
	Exceeding the initial project cost	$
	Design change costs	$
	Costs of modifications related to the customer's request	$
	Costs of modifications related to the site conditions	$
Time	Speed of project delivery (design and construction)	m^2/days
	Speed of project design	m^2/days
	Exceeding deadlines	days
	Change processing time	days
	Number of design-related changes	#
	Number of changes related to the customer's request	#
	Number of changes related to the site conditions	#
Labour productivity	Effort by area	h/m^2
	Effort by project phase by area	h/m^2
	Effort per project phase by fees	h/$

Adapted from Coates et al. [10], Barlish and Sullivan [1], Abdirad [12]

Table 2 Summary of qualitative KPIs

Metrics	Qualitative KPIs	Unit
Maturity of the staff	Maturity level of staff by position	#
	Number of people per project	#
Access, understanding and sharing of information	Number of sheets/m^2	#
	Number of sections and details per m^2	#
	Number of files	#
	File size (total)	MB

Adapted from Coates et al. [10], Barlish and Sullivan [1], Abdirad [12], Renzo Piano (presentation at CanBIM, April, 2019)

must be encouraged by empirical evidence, while investors must see clear evidence of its benefits to justify their investment of time and money [14]. Currently, there is no standard method for calculating the ROI of BIM. Many companies have not adopted consistent measurement practices, although they have an interest in doing so, given the benefits of considering ROI in BIM investment decision making [4]. In this research, four methods of assessing BIM performance were explored, namely: (1) a framework methodology to quantify the benefits of BIM [1]. (2) the calculation of the costs/benefits of BIM implementation using the time-effort distribution curve [13]. (3) Autodesk Revit's method for measuring ROI [5]. (4) the cash flow formula for the return on investment of BIM [15].

The objective of the methods proposed is to empirically measure the performance of the BIM implementation. The first method aims to develop a framework methodology to quantify the benefits of BIM. In addition, this method consists of establishing KPIs to compare projects with BIM and without BIM to build a business case for the benefits of using BIM. However, this method does not use a mathematical formula to directly calculate the ROI of BIM. The second method aims to calculate the cost/benefit of BIM by demystifying the time-effort distribution curves of AEC processes in real-life situations. The method consists of developing a model using MacLeamy's time-effort distribution curve based on empirical data on two projects from the same company, one with BIM and one without BIM. Thus, this method supports, to some extent, the argument that a slight increase in design effort through the implementation of BIM will significantly improve the execution of a project. However, the unavailability of data in terms of time and effort, given that data collection in BIM projects is still sporadic in the industry, presents an obstacle to the application of this method. The third and fourth methods aim to calculate the ROI of BIM using mathematical formulas. These methods estimate software and labour costs, productivity losses and growth, and training time. However, the difficulty in measuring productivity presents a barrier in using both methods. Finally, considering the availability of data, the first method is the most appropriate for our research. This method is consistent with the problem statement of this report, to fill the gap of a balanced framework for the implementation of BIM that considers both monetary and management outcomes.

3 Methodology

The objective of this section is to present the methodology used in this project, which is the action research approach to assess the viability of BIM deployment in an architecture firm. This approach is best suited to our needs because of its iterative approach and its interventionist nature within the research framework, which offers the possibility of generating knowledge about a system while trying to change it [16]. Action research is an iterative process composed of 5 distinct phases, as explained by Azhar et al. [17] and Baskerville and Pries-Heje [18]: Diagnosis, Action planning, Taking actions, Evaluation and Validation and Lessons Learned.

To ensure the necessary rigor in the analysis, action planning is based on four steps: observation, document review, informal meetings and discussions, and a focus group (Table 3). The complementary nature of the data collected through these 4 steps makes it possible to build the analysis.

Action research aims to construct and test a theory in the context of solving an immediate practical problem in a real-world context. To this end, research work is framed academically and empirically. Academic supervision supports the research with a reliable database built from relevant scientific literature, as well as the curriculum of BIM courses taken at the university. Empirical supervision, within the firm, supports research through empirical data collected via the servers, as well

Table 3 Action research action planning

Steps	Involved collaborators	Month 1	Month 2	Month 3	Month 4
Step 1: Observation	– Architecture project team – Commercial project team – BIM managers	(Continuous)			
Step 2: Document review	– Project managers – BIM managers	80 days			
Step 3: Meetings, presentations, and informal discussions	– Project managers – BIM managers	80 days			
Step 4: Focus group	– Project managers – BIM managers – Architecture project team – Commercial project team				1 day

as through the experience and opinions of the people involved in the project. Then, the data will be analyzed and tested by comparing projects (BIM with no template vs. non-BIM) to evaluate the impact of BIM on these projects and thus measure the performance of BIM in the firm. Seven (7) projects proposed by the firm are studied, including 5 architectural projects (residential) and 2 commercial projects.

- Architectural projects (residential):
  - Project 1. RES 1; realized with AutoCAD (without BIM),
  - Project 2. RES 2; realized with CAD and the BIM approach (Revit, without template),
  - Project 3. RES 3; carried out using the BIM approach (Revit, with template),
  - Project 4. RES 4; carried out using the BIM approach (Revit, without template).
- Commercial projects (stores):
  - Project 1. STO 1; realized with AutoCAD (without BIM),
  - Project 2. STO 2; realized with the BIM (Revit) approach.

Project comparisons will be made using the metrics identified in the literature and tables that present cost, time, and labor parameters (Table 4). The purpose of the comparative analysis is to assess the impact of the use of BIM on the projects and on the metrics used. The comparison of housing projects will be done separately from commercial projects.

- **Focus group**:

The purpose of this step is to finalize the collection of case study data. The Focus Group is a qualitative research method that encourages the emergence of all opinions.

Table 4 Explanatory table of the comparison

Type of project	Architectural projects (residential)				Commercial projects	
Project Name	Project 1	Project 2	Project 3	Project 4	Project 1	Project 2
Comparison	Cost parameters				Cost parameters	
	Time parameters				Time parameters	
	Labour parameters				Labour parameters	

This method is both oral and group-based, it allows the collection of perceptions, attitudes, beliefs, areas of resistance of the target groups. It answers the "why" and "how" questions.».

It is a meeting of about 90 min whose objective is to present and validate the results of the documentary analysis and to complete the analysis with a qualitative study on the satisfaction and challenges encountered in each project. The targeted people are the project managers and some of the people involved in the BIM process. The Mentimeter application was used to complete the qualitative study. This free online application allows you to create interactive presentations by asking questions and showing the results of the answers of an audience instantly.

4 Results and Discussion

4.1 Benchmarking of Projects

As mentioned earlier, seven projects were selected by the firm for this study, including five architectural projects (residential) and two commercial development projects (stores). In this section, the raw data collected for each case study project is presented and analyzed. Table 5 provides an overview of the seven projects observed, grouping their main characteristics (mode of delivery, cost, time frame, level and unit, area) and their use of BIM.

4.2 Qualitative Study: Focus Group

The first part of the focus group made it possible to validate and justify the quantitative and qualitative data collected via the firm's servers and previously presented in the comparative analyses. The second part of the focus group provided an overview of the individual perspectives of the project managers and assessed their experiences and the general atmosphere of the BIM environment within the company. The raw data from the focus group did not contribute to the calculation of the BIM ROI, but rather served as contextual information. Using the Mentimeter application, participants

Table 5 Summary of the seven projects

Type of project	Architectural projects (residential)				Commercial projects	
Project name	RES 1	RES 2	RES 3	RES 4	STO 1	STO 2
Technology	Without BIM	AutoCad+BIM	With BIM	With BIM	Without BIM	With BIM
Method of realization	Design-build	Fixed-price contract	Fixed-price contract	Design-build	Fixed-price contract	Fixed-price contract
Gross built area	700,880 m^2	641,940 m^2	1,409,100 m^2	3,268,000 m^2	667 m^2	7464 m^2
Level and unit	3 floors/74 units	3 to 4 floors/57 units	4 floors/124 units	7 to 13 floors/313 units	RDC	RDC
Costs in $$	10,5 M	7,8 M	20,8 M	54,9 M	N/D	N/D
Delay in days	N/A	N/A	N/D	N/D	123	114

were asked to answer questions about the satisfaction and challenges encountered, internally and externally, when using BIM in projects. Six people from the firm (project managers) participated in this study.

4.3 Results and Discussion

This search produces several results: First, the comparison of cost overruns in architecture projects showed that the project carried out in BIM is more efficient (Fig. 1).

This is the case of the RES 3 project, with BIM, which is 3.7% over the initial cost of this project. This is despite its complexity compared to other projects. This result validates what is advanced in the literature by Coates et al. [10], namely that the use of BIM allows better cost control. Nevertheless, this comparison was only possible for the RES 3 projects (with BIM) and the RES 2 (with AutoCad and BIM).

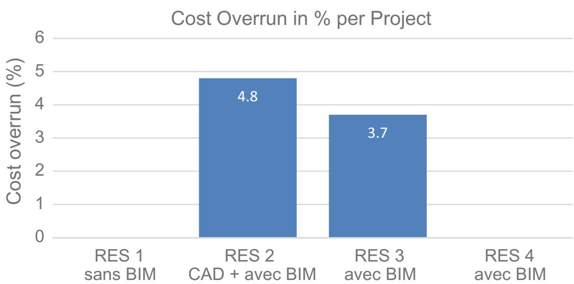

Fig. 1 Cost overruns by project

A comparison of cost overruns for projects without BIM and with BIM was not possible due to the different nature of the project delivery mode. However, it should be noted that the use of BIM contributes to a reduction in costs associated with design changes, which is a tangible result of reduced errors and omissions in documents, again reducing risk and improving productivity [6]. This reduction in design change costs is not analyzed due to a lack of data.

Second, by comparing the speed of production of commercial project execution plans, it was found that the BIM project performed best (Fig. 2). This result is in line with what was argued in the literature by Coates et al. [10] and Abdirad [12] that the use of BIM improves the speed of services provided by the company. It should be noted that the speed of production of execution plans for architecture projects has not been analyzed due to a lack of data.

Third, in terms of the labor effort required, BIM projects typically have the lowest number of hours per area (Figs. 3 and 4). This is the case for RES 4 (architectural) and STO 2 (commercial) projects. The results for these two projects confirm what has been advanced in the literature, according to McGraw-Hill [6], the use of BIM helps to optimize workflow and improve productivity, which is a goal for architects.

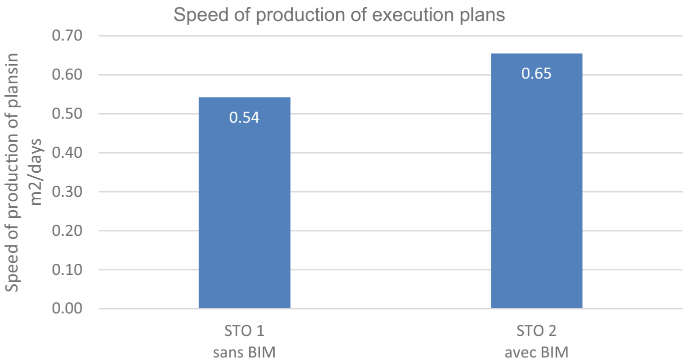

Fig. 2 Speed of production of project execution plans

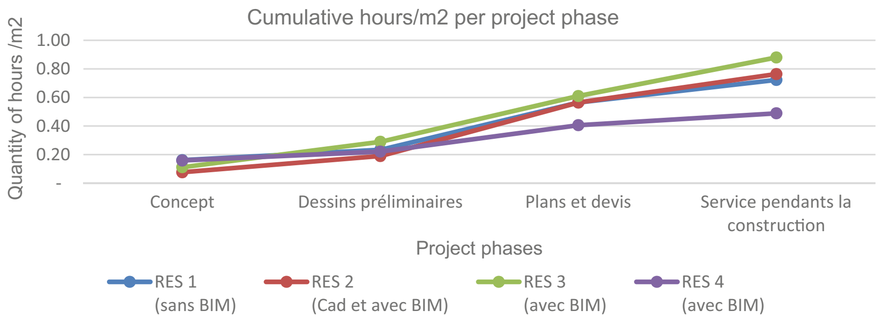

Fig. 3 Comparison of cumulative hours per area by phase of architectural projects

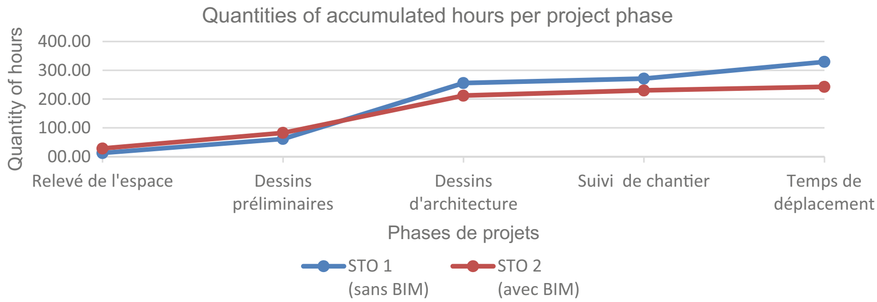

Fig. 4 Graphical representation of the comparison of cumulative hours from commercial projects

However, implementing BIM entails additional costs and requires ongoing investments in hardware, software, training, and processes to realize their potential value [13]. Not surprisingly, in both projects, RES 2 (CAD, with BIM) and RES 3 (pilot project, with BIM), BIM implementation resulted in many hours for the company compared to the RES 1 (without BIM) and RES 4 (with BIM) projects. Also, this was due to the tight deadlines for the delivery of two projects, as well as their complexities.

Fourth, the focus group results, and the comparison of qualitative data showed that the use of BIM in projects has many advantages, namely:

- Reduced travel, printing, and shipping costs.
- Improved collaboration and information sharing among stakeholders.
- Better communication and improved information and workflow management.
- An efficient visualization, coordination, and validation tool.
- A means of prior detection of interferences to avoid possible problems.
- A competitive advantage for companies during the tendering phase and an increase in the number of project invitations to tender.
- Greater respect of costs and deadlines, which increases customer satisfaction.
- Reduced errors and lost time and increased staff productivity.

Finally, the assessment of BIM maturity levels in relation to effort showed that, the greatest effort to produce the mock-ups is made by employees with a low level of BIM maturity. This is due to the lack of BIM experience and knowledge of these employees, which results in the high number of hours worked. However, better project performance requires the use of more mature BIM resources. Hence the importance of investing efforts in training.

5 Conclusion and Future Work

The main objective of this action-research was to define and validate a method to empirically measure the ROI of BIM implementation in an architectural firm. The results of this approach present a relevant assessment for the use of BIM and generally confirm what has been advanced in the literature, namely: the importance of predefined performance indicators (KPIs) in the BIM implementation strategy and the quantification of benefits in the assessment of the ROI of BIM. The success of BIM depends on many factors such as project complexity, employee BIM skills, project delivery modes, as well as other factors external to the company. The data collected for the case studies shows better performance of projects with BIM compared to projects without BIM. In the course of this work, tangible and intangible metrics impacting the labour productivity, time and cost of project delivery were examined through four BIM use cases to measure BIM ROI. Also, qualitative data was collected via a focus group to provide insight into the individual perspectives of employees and to assess their experiences and the general atmosphere of the BIM environment within the company. The results of the benchmarking studies suggest that the use of BIM helps to better control project costs, reduce the speed of project execution plans, help optimize workflow and improve employee productivity. The results of the focus group show not only the intangible benefits of using BIM in projects, such as improved understanding and visualization of the concept, better collaboration between stakeholders and customer satisfaction. But also, the obstacles encountered, such as the difference in the BIM maturity level of teammates, non-compliance with BMP and BIP and resistance to change.

Several points remain to be considered as limits to our project and our analysis. The scope of this study has been narrowed as much data was not available for some projects, as data collection for BIM projects is still sporadic within the firm. Many data could not be found, despite the cooperation of the project officers in locating them. For example, the lack of timelines for architectural projects and the lack of cost data for commercial development projects limited the analysis of costs and timelines for BIM projects. Also, the absence of data such as BIM investment costs (initiatives completed, training and IT infrastructure, etc.) and project fees limited the use of ROI formulas proposed in the literature. Another limitation of the work was the choice of architectural projects for comparison purposes. It is often difficult to collect data on actual construction projects. Because of their one-time and irreversible nature, it is often difficult and too costly to study them in a comparative analysis that involves, for example, setting up treatment and control groups and obtaining experimental data. The temporary nature of project teams further complicates data collection. Ideally, identical projects that differ only in the BIM implementation factor should be found for comparison. However, variables such as project type, delivery mode, project complexity, and employee skills make each site unique. In addition, there is a degree of uncertainty in observing BIM maturity levels in relation to employee effort due to the inability to separate production and project management tasks for employees, and to differentiate employee training hours in each project. Finally, this study presents the first case for evaluating BIM performance, so the results found cannot be generalized to all the firm's projects.

This research project was intended to be exploratory, given the constraints related to the limited scope of an application project and the difficulty of collecting relevant data. The work carried out may therefore open the door to further research to refine the overall benchmarking and performance assessment strategy presented in Chap. 3, including a similar study on more projects (see if possible, all BIM projects within the agency), to establish a complete mapping of the company. Finally, the results of this action research should serve as a basis for developing a strategy to be implemented to allow the evaluation of the return on investment in construction innovation projects.

The recommendations to the industrial partner to better measure the return on investment of the actions undertaken to improve the performance to produce the models are the following:

- Deploy efforts to reduce the variability and uniqueness of projects so that they are comparable, if not entirely identical,
- Collect data on project costs, time, and effort. These data will form the basis for comparing projects with and without BIM. The KPIs to be used for the comparison are costs (in \$ or \$/m^2), project delivery and design speeds (in m^2/day) and labour effort (in hours or h/m^2).
- Cross-reference the efforts (in hours or h/m^2) with the fees (in \$) of the projects to evaluate employee productivity.
- Take into consideration employee training time during projects.
- Identify maturity levels in three categories: management, production, and coordination. In this way, the assessment of maturity levels will be accurate and reflect the reality of the firm's understanding of BIM and its training needs.
- Homogenize the recording of time sheets according to project phases, namely: concept, preliminary drawings, plans and specifications and site supervision. To this end, the BIM cost/benefit calculation can be performed.
- Track the number and cost of amendment amendments with their causes and record the processing time for each amendment.
- Compare the number of hours per building envelope area.
- Use the BIM ROI cash flow formula to determine the annual financial impact of BIM implementation.

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A Framework to Evaluate School Infrastructure Project Need Using Fuzzy Expert System

Monjurul Hasan and Ross Newton

1 Introduction

During the last decade, there has been significant infrastructure investment around the world in school building projects either for new buildings or renovations. Canada is no exception. The government, like other public agencies, funds school capital projects to address evolving capacity needs due to student growth, changes in regional demographics and boundaries, meeting the improvements necessitated by operating half a century-old building system and recognizing the need for an improved facility to provide a twenty-first century learning environment to the students. In the last few years, three major Canadian provinces (Ontario, British Columbia, and Alberta) have invested more than a billion dollars in school projects. The Ontario government is investing over $500 million to build 30 new schools and make permanent additions to 15 existing facilities across the province [1]. The British Columbia government announced funding of $339 million over three years to support the kindergarten to grade-12 education system [2]. Alberta's government announced $397 million in 2019 for 25 school projects [3].

Maintaining and building new infrastructure that delivers agglomerative benefits is crucial for promoting sustainable economic growth. Capital projects for infrastructure projects are large, and funding opportunities are often limited [4]. Therefore, in order to achieve the highest number of positive outcomes, capital investors—like the government, need to prioritize projects based on the criticality of need. This phenomenon raises the need to rely on a set of selection criteria for prioritizing a number of projects when making funding considerations. Essentially, those projects

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with the most favorable scores are considered the highest priorities. However, the core question remains the same, "how to select projects?" When making decisions regarding the funding of school capital projects, it is also imperative to simultaneously compare it with other capital needs (e.g., roads, refineries, hospitals, utility service infrastructure, etc.). Therefore, assessing the need with quantifiable terms for any school capital project is deemed critical for decision making. There are many published materials outlining the methodology to select public sector projects [5]. Some government entities have published numerous high-level frameworks for selecting a public-infrastructure project. While a vast amount of work is being published to prioritize capital projects, school building projects have a unique type of need that is often difficult to measure when it comes to their return on investment. Despite the fact that these projects require substantial investments, little analytical work has been done to measure the needs, their benefits and prioritize them accordingly.

This paper reports a methodological approach for a consistent and transparent way of quantifying a project's need and scoring the project accordingly. The attributes that contribute to the assessment of school infrastructure project needs have been identified by consulting with domain experts. Based on the attributes identified, a fuzzy expert/rule-based system has been developed to automate the process of assessing the school infrastructure project needs. The application of the framework is presented with example cases. Even though the proposed framework is developed in the context of the Canadian environment, the method presented in this paper can be applied as a general framework for evaluating school project needs around the world.

2 Background

It is vital to identify the correct information processing system in any decision-making process to analyze and prioritize a project's need [6]. According to Badri et al. [7], there are thirteen types of methods raised for construction project selection decision-making, including scoring, ranking, mathematical programming, fuzzy logic, and analytic hierarchy process (AHP). Project prioritization based on the cost analysis (present value and payback) is suggested by Okpala [8]. Odusote and Fellows [9] proposed a non-weighted ranking process to rank the project investment decision. While in 1996, Gori [10] showed a mathematical programming approach to select infrastructure projects. In the same year, Alidi [11] proposed the analytical hierarchy process to quantify the project viability. Later, Molenaar and Songer [5] proposed a multi-attribute analysis in conjunction with regression models to select the public sector design-build projects. A fuzzy AHP-based methodology for project prioritization and selection process is also suggested by Shaygan and Tesik [12]. Despite the methodology being proposed, the researchers agree that the infrastructure project selection process is a multipartite decision-making problem [13] that depends on numerous variables. The review done by Hansen et al. [14] concluded that 34 decision criteria are further clustered into five major groups that have been used on different occasions to select and prioritize infrastructure project proposals, which are: (1) strategic fit, (2) owner philosophies, (3) project funding and timing, (4) project requirements, and (5) value engineering. For finding the appropriate score to resemble the strategic fit, the most important thing is to quantify the project's need and purpose in a quantifiable term. However, to the author's best knowledge, there is no formal literature published so far that describes the methodology to quantify the project need, especially for school capital projects.

Numerous variables influence school project needs, and most of them are subjective and better expressed in linguistic terms. Moreover, limited data is available to structure the correlation between the variables and outcome score. Most of the quantification method depends on the expert's knowledge and mental model. In this context, fuzzy logic and a fuzzy expert system, which is capable of handling subjective variables and representing expert's knowledge by fuzzy inference system, is the best fit for solving the problem [15].

3 Model Structure

3.1 Input and Output Variables

The evaluation of a school capital project need requires the identification of a set of parameters (input variables) that are considered indispensable to its construction. The input variables for this model are identified by conducting a series of semi-structured interviews with three professional experts with over 15 years of experience in school capital project planning. The participants were asked to provide a comprehensive list of parameters and definitions they considered crucial for evaluating the need for a school capital project. A total of 18 parameters were compiled from the interviews. After the interviews were complete, a comprehensive list of the parameters along with their definitions was sent to the participants. They were asked to assign a relative score to each parameter on a scale of 0 to 10, with 0 implying null significance and 10 identifying the highest significance. Average scores were calculated for individual parameters. Parameters that received an average score of five and above are considered in the development of the model to predict the school project need score (output variable). Table 1 shows 14 parameters (out of 18) that are used for modeling purposes.

Area capacity utilization (ACU) of schools, the average ride distance and the average ride time of the school students can be found using the Eqs. 1, 2, and 3, respectively.

$$\text{ACU} = \frac{\sum \text{Adjusted total school student enrollment}}{\sum \text{Net school capacity}} \tag{1}$$

Table 1 List of input variables for evaluating school project need

No	Parameters	Input score range	Average weight
I1	Current area capacity utilization (ACU) of the education sector (all grades: K—12) of a community	0–1.5	5.3
I2	Current ACU of neighbourhood—all grades (K—12) of a community	0–1.5	6.0
I3	Current ACU of neighborhood—specific grades (e.g., K—6, 7–9, 10–12) of a community	0–1.5	7.7
I4	Projected (5 years) ACU of education sector of a community	0–1.5	6.7
I5	Projected ACU neighbourhood—all grades of a community	0–1.5	7.3
I6	Projected ACU neighborhood—specific grades of a community	0–1.5	9.7
I7	Average ride distance for sector school students—all grades of a community in kilometre (s)	0–20	7.7
I8	Average ride distance for sector school students—all grades of a community in kilometre (s)	0–20	8.3
I9	Average ride distance for neighborhood school students—specific grades of a community in kilometre(s)	0–20	9.0
I10	Average ride time for sector school students—all grades of a community in minutes(s)	0–40	6.7
I11	Average ride time for neighborhood school students—all grades of a community in minutes(s)	0–40	7.3
I12	Average ride time neighborhood school students—specific grades of a community in minutes(s)	0–40	8.3
I13	Student population growth rate in the community (neighborhood)	(−10)–(+10)	8.7
I14	Legal Need score (here, 0: no need, and 10: must address now)	0–10	9.7

$$\text{Average ride distance} = \frac{\sum \text{Distance from student's residence to school}}{\text{Total student number}} \tag{2}$$

$$\text{Average ride time} = \frac{\sum \text{Time required to travel from student's residence to school}}{\text{Total student number}} \tag{3}$$

Here, “net school capacity” and “adjusted student enrollment” calculation details can be found in the school capital manual of Alberta [16].

It is worth noting that student population projections play a vital role in assessing the school capital project need. There are various approaches available in the literature for multi-regional population prediction for different age groups [17]. For the purpose of student population prediction, a modified version of the West Yorkshire model is being used in this paper [18]. A conceptual version of the population prediction model is provided in Eq. 4; however, its construction is beyond the scope of this paper.

$$P_t = f(P_0, D_0, E_0, I_0, Out_0, In_0, B_0); \tag{4}$$

where:

P_t = student population of a neighbourhood at the end of projection year, t.

P_0 = population at the start of the projection, and D_0 = deaths estimate during the time interval.

E_0 = the number of emigrants, and I_0 = surviving immigrants.

Out_0 = the number of internal out-migrants, and In_0 = surviving in-migrants.

B_0 = the number of surviving births.

The parameter "Legal Need" for a school project becomes active where there is a rule (legislation) that is advisable or required to observe regarding a specific group of students. The severity of the legal need increases as the student population increases. Equation 5 is used to quantify the Legal Need score.

$$\begin{aligned} \text{Legal Need Score} &= \frac{\text{Number of students}}{25}; \\ \text{Legal Need score} &= 10, \text{ if Number of students} \geq 250. \end{aligned} \tag{5}$$

For the parameters referring to community, neighborhood defines the area from where the school(s) draw their student population, and a sector may involve multiple neighborhoods. In assessing the need for a new school, both sector schools and neighborhood schools should be considered. If the sector school has a lower utilization (ACU) rate than a particular neighborhood, additional student spaces (capacity) requirement can be met by rezoning (changing the student catchment area). Considering the area capacity utilization rate of all grades vs. specific grades is also important because it provides the opportunity for grade reconfiguration to neighborhood schools to alleviate the student enrollment pressure.

3.2 *Model Organization*

After identifying the main input parameters against the output variable, the model is structured further by putting the input variables into groups and subgroups

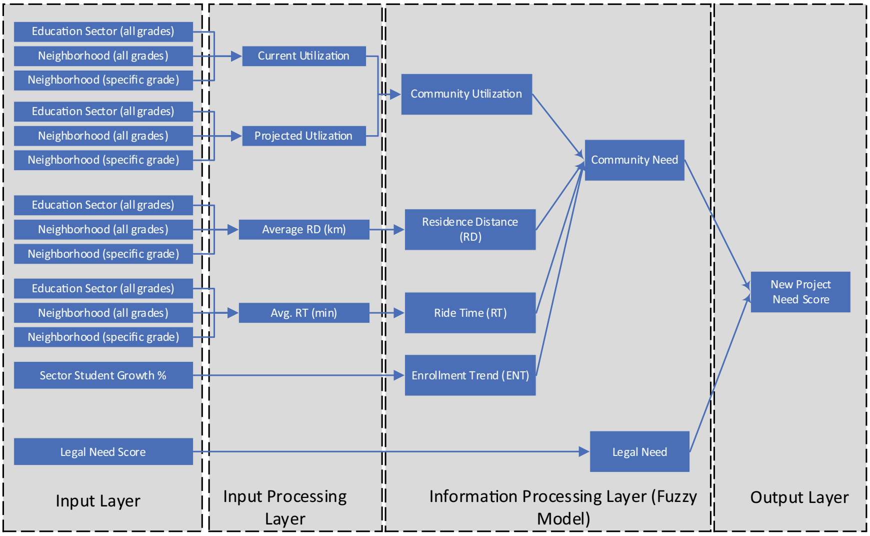

Fig. 1 Structure of model for evaluation school capital project need

under common themes. These groupings have made the model more organized and condensed the rules to persuade it to a fuzzy expert system. Figure 1 represents the complete version of the model and shows the relationship between input variables. This figure shows the project output variables separated into two prime groups: community need and legal need. The "community need" prime group can be further divided into four subgroups, "community utilization," "residence distance (RD)," the "ride time (RT)," and "enrollment trend (ENT)." In order to obtain the estimate of these subgroup variables, corresponding input variables (input for jurisdiction-all grades, neighborhood-all grades, and neighborhood-specific grades) have been aggregated in the input processing layer.

4 Generating the Membership Function

For the school capital project evaluation/scoring model, a family of fuzzy sets has been formulated based on the experts' firsthand input. First, each variable (input, subgroup, prime group, and output v) is expressed by three membership functions, low (L), medium (M), high (H). However, the variable "student population growth rate" was expressed by decreasing (D), stable (S), and increasing (I) membership functions. Next, the shapes and ranges of the set of membership functions (L, M, H) for each variable are determined. The three individual experts were asked to provide numerical ranges for L and H of each input, output, and subgroup variable. Maximum and minimum membership grades are assigned to each membership function (L

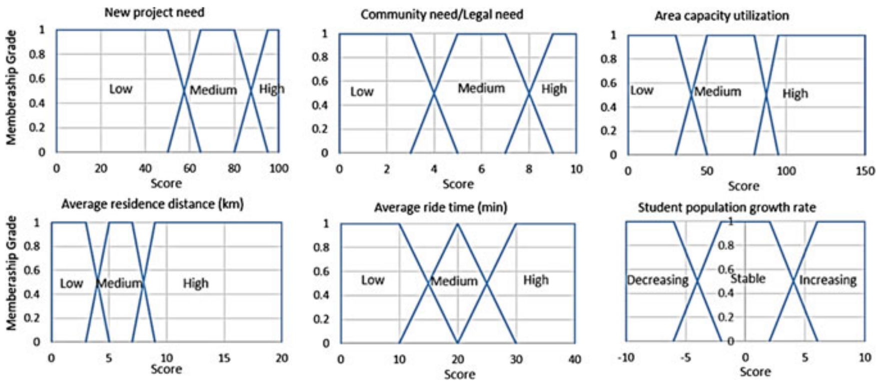

Fig. 2 Fuzzy input and output variables

and H) based on maximum experts' responses (i.e., frequency of each value). Then the medium membership function is placed to overlap with both the low and high membership functions. Accordingly, triangular and trapezoidal shapes are adopted, as shown in Fig. 2. Details of the input variable definition and input ranges are provided in Table 2. Note, input ranges of all prime group variables varies from a scale of 0 to 10.

5 Generating Fuzzy Expert Rules

There are several methods to generate the if–then rules for fuzzy expert system, and most of them are data-intensive [19]. However, the limitation of the data availability makes all those previous studies unsuitable to adopt here. Instead, a modified version of the approaches proposed by [20] and Fayek and Sun [21] has been adopted to generate the fuzzy expert rules in this study. While developing the fuzzy rules, it was considered that all the input parameters (fuzzy variables) are independent and have an equal effect on the output. Therefore an "and" operator was used as the joining operator in the premise of each rule. The procedure for creating fuzzy expert rules are as follows.

Since there are multiple levels of input and output variables interacting with each other in the proposed model, the first step is to select one attribute (subgroup variable) and identify the input variables for that particular attribute. For example, for the output variable new school need, there are two input variables: community need and legal need.

Second, the number of rules requires that a complete rule base is calculated. The number of rules should be equal to the multiple of the number of membership functions for all input variables. For example, the output variable, new school need is generated from two input variables: community need, and legal need, and there are

Table 2 Fuzzy knowledge base for output variables

Output variables	Status	Outcome
Knowledge base: new project need		
Community need	L	L
	M	M
	H	H
Legal need	L	L
	M	L
	H	H
Knowledge base: community need		
Community utilization	L	H
	M	M
	H	H
Average residence distance	L	L
	M	M
	H	H
Ride time	L	L
	M	M
	H	H
Enrollment trend	D	L
	S	L
	I	M

three fuzzy (i.e., L, M, and H) membership functions that define each input variable. Therefore, the total number of rules will be $3 \times 3 = 9$. For the subgroup variable, "community need" total number of rules will be $3 \times 3 \times 3 \times 3 = 81$(four input variables with three membership functions for each).

The third step is to create the knowledge base to link input variables to their output variables with experts' direct consensus opinion. A complete knowledge base for output variables "New project need" and "Community Need" is given in Table 2.

The fourth step is to create decision rules depending on the knowledge base made earlier. In order to compose the fuzzy rules, scores of 1, 2 and 5, are given to the suitability indicator "low," "medium," and "high," respectively. When a rule is composed, the sum of the scores of the preconditions are determined and compared to a set of values for input variables that relates to the condition of "low," "medium," and "high." For example, for "new project need," there are only two input variables. If the sum of the score value reaches the threshold of six, the conclusion for this rule is the need is "high;" if the score value rests between three to five, the need is Medium; for any score value below three, the project need is Low. The cut-off values for each combination of input and output variables to construct expert rules are determined on a case-by-case basis. In conversation with the experts, generated rules were also verified after construction. Table 3 summarizes all the rules created

Table 3 Fuzzy rules for evaluating output score of variable "new project need."

No	Community need (i)	Legal need (ii)	Score			Outcome
			(i)	(ii)	Sum of (i) and (ii)	
1	L	L	1	1	2	L
2	L	M	1	1	2	L
3	L	H	1	5	6	H
4	M	L	2	1	3	M
5	M	M	2	1	3	M
6	M	H	2	5	7	H
7	H	L	5	1	6	H
8	H	M	5	1	6	H
9	H	H	5	5	10	H

Note If sum $\geq$ 6, then outcome = H; If 5 $\geq$ sum $\geq$ 3, then outcome = M, and otherwise, outcome = L

to assess "new project need," and a representative sample of rules created to get the "community need" score is given in Table 4.

Step 1 to 4 are followed to create rules for different compositions required for the capital planning need assessment model.

6 Generating Static Weight for Linear Relationship

As mentioned earlier, some of the input variables require pre-processing before fuzzifying themselves. This pre-processing needs to aggregate some variables together by weight. For example, current community utilization has three parts: ACU for sector schools—all grades, ACU for neighborhood schools—all grades, and ACU for neighborhood school—specific grades, as shown in Fig. 1. Therefore, the current community utilization rate is calculated by taking the weighted sum of three individual input variables. The weight of the corresponding input variables for this calculation is generated using the experts' average priority score as listed in Table 1 and following analytical hierarchy process (AHP) [22]. The consistency of the generated weights is also checked. All weights generated for different variables are listed in Table 5.

7 Evaluating the School Infrastructure Project Need

With the membership functions and fuzzy rules formulated, it is possible to use them with specific values of the input variables to compute a numeric value of the output variable. This process is known as the fuzzy rule-based inference [22].

Table 4 Fuzzy rules (representative) for evaluating the output score of variable "community need"

No.	Community utilization (i)	Average residence distance (ii)	Ride time (iii)	Enrollment trend (iv)	Score					Outcome
					(i)	(ii)	(iii)	(iv)	Sum	
1	L	M	L	D	1	2	1	1	5	L
2	L	M	L	S	1	2	1	1	5	L
3	L	M	M	D	1	2	2	1	6	L
4	L	M	M	S	1	2	2	1	6	L
5	L	M	M	I	1	2	2	2	7	M
6	L	M	H	D	1	2	5	1	9	H
7	L	M	H	S	1	2	5	1	9	H
8	L	M	L	D	1	2	1	1	5	L
9	L	M	L	S	1	2	1	1	5	L

Note If sum ≥ 9, then outcome = H; If $8 \geq$ sum ≥ 7, then outcome = M, and otherwise, outcome = L

Table 5 Weight values used for different input variables

Variable Group	Input Variable	Weight	Multiplier
Current Utilization	Jurisdiction	0.27	0.45
	Sector	0.34	
	Neighborhood	0.39	
Projected Utilization	Jurisdiction	0.28	0.55
	Sector	0.31	
	Neighborhood	0.41	
Average RD, and Average RT	Jurisdiction	0.30	1.00
	Sector	0.33	
	Neighborhood	0.37	

The fuzzy expert system is implemented using MATLAB Fuzzy Toolbox [23]. The system used the "min" (minimum) operator in the premise of rules, the min–max (minimum–maximum) method for rule implication-aggregation, and the centroidal method for defuzzification. Besides, equal weight (=1) is given to all rules. Here, the centroidal method is chosen rather than bisection or largest of maximum (LOM), middle of maximum (MOM), and the smallest of the maximum (SOM). The reason is, the centroidal method accounts for all the rules that are being fired and considers them in defuzzification as per their weight (membership grade). The typical steps used in a fuzzy rule-based system can be summarized as follows:

- Input the numeric values for all 14 input variables as listed in Table 1.
- Fuzzy inputs are processed into the subgroup levels by the fuzzy operator of the inference system.
- The fuzzy minimum implication method is applied to estimate the firing strength of each rule to determine how much the consequence of a rule contributes to the output value.
- Aggregate the consequences of all rules to form the overall membership function of the output variables.
- Defuzzify, the overall membership function, to convert it to a crisp (non-fuzzy) value through a defuzzification process.
- This process continues at each level for subgroup variables until it reaches the final output variable. Defuzzified output from one level is used as the input for the next level. For example, a defuzzified output score from the "community need" subgroup level 2 is used as the input variable for finding the new project need (output variables).

8 System Validation

A total of five projects are used for evaluation, and the input parameters for each project are summarised in Table 6. First, these projects were evaluated by experts, and the outputs (project needs) were recorded in linguistic terms. The model developed in this paper is then used to predict the need score. The corresponding linguistic variable is used to describe the need. The forecasted needs scores of the model are compared to the expected needs of the experts. When the need score falls under two membership functions, the maximum strength of the membership functions is used in the comparison. The results of the comparison are shown in Table 7. According to the comparison result, the model can accurately predict the right scale of need in linguistic terms. Considering the membership value for all expert decisions is equal to 1.0, the accuracy of the model was around 98% (error 2%).

Table 6 Input variables for the test cases

Variable ID	Case 1	Case 2	Case 3	Case 4	Case 5
I1	0.74	0.96	0.74	0.74	0.96
I2	0.82	1.04	0.82	0.82	1.04
I3	0.85	1.06	0.85	0.85	1.06
I4	0.80	1.10	0.80	0.80	1.10
I5	0.93	1.20	1.04	1.04	1.20
I6	0.94	1.04	1.04	1.04	1.04
I7	4	4	14	11	8
I8	8	5	20	12	9
I9	7	5	21	14	9
I10	9	31	31	28	8
I11	10	30	29	30	10
I12	10	25	35	30	9
I13	3	−3	10	15	−10
I14	10	0	0	0	0

Table 7 Actual and predicted result comparison in linguistic terms

Case ID	Score: new	Need in linguistic term	Degree of membership as identified by the model	Need identified by experts (membership grade = 1.0)	Error in decision
1	93.28	High	1.00	Medium	0.00
2	89.18	High	0.89	High	0.01
3	90.29	High	1.00	High	0.00
4	72.50	Medium	1.00	Medium	0.00
5	91.52	High	1.00	High	0.00
Average decision error					0.002

9 Conclusion

This paper presents a comprehensive framework for evaluating any new school project needs in quantifiable terms based on the fuzzy expert system. The notable contributions are to formalize a methodology to identify the essential variables for qualifying the project need and show how to use those variables for need assessment of school capital projects. The need score can be used to compare projects with each other and for ranking. This paper also shows how fuzzy set theory can be used to represent subjective variables. The proposed fuzzy expert model was face-validated with the experts first. Test results showed around 98% accuracy when the prediction results were compared with the experts' actual score in linguistic terms. Even though the proposed framework is developed in the context of the Canadian environment, the method presented can be applied as a general framework worldwide for evaluating the school project needs by any authorities or agencies. This research's primary limitation is that the model is formulated using a limited number of experts who have work experience with the same public agency. Exposing the model to a large number of domain experts (work experience with diversified capital planning agencies from different geographic locations) could identify other variables missed in this study. However, the methodology presented here remains valid, and new input variables can be adapted to the system by following the step-by-step procedure described here. No correlation analysis among input variables has been done due to a lack of data. The author intends to perform correlation analysis with a substantial data set to refine the model and then test the model against an extensive data set in the near future.

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Decision Support System for Fast Provision of Healthcare Facilities in Response to COVID-19 Pandemic Outbreak

D. A. Saad and M. M. Hassan

1 Introduction

Amid the peak of the first coronavirus wave, healthcare facilities (HCF) were overwhelmed worldwide with the number of positive cases that needed hospitalization. For instance, countries such as South Korea faced severe hospital bed shortage leading to patients dying at home while waiting admission [26]. In Italy, the hospitals were overwhelmed with cases in just three weeks due to the rapid surge in cases [21]. In the second wave, due to the morbidity of the virus, the number of positive cases has even increased more. For instance, United States had a very high record of almost 300,000 positive case per day. With the massive influx of COVID-19 patients, healthcare facilities became overwhelmed creating an urgent need for providing additional inpatient care facilities [16]. Some countries are adopting several interventions to increase health care capacity. For instance, in England, several interventions were considered, including cancellation of elective surgery, set-up of field hospitals, deployment of newly qualified/final year medicine and nursing students, and return of former healthcare staff [29]. However, to increase the capacity of HCFs, construction of new hospitals, and conversion of existing facilities into temporary patient care facilities have been most commonly used [18, 34].

Fast construction of new healthcare facilities has been studied for decades to quickly accommodate the increasing demand for medical care, yet mostly using prefabrication and off-site construction techniques [1]. Recently, these techniques

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alongside excessive resources were used to build a temporary hospital, Leishenshan hospital, of 2000 beds in China in 10 days [10]. However, new COVID-19 build could be quite costly and time consuming [34]. Moreover, it will need special requirements to be suitable for hosting COVID-19 patients in a cost-effective and timely manner. Several parameters need to be considered, including: design-related medical requirements, sustainability, construction time and cost, life cycle costs, location of the prospective facility, etc. Therefore, there is a need for a proper analysis of the potential alternative structural systems to help make a responsible decision.

On the other hand, conversion of non-medical facilities (NMF) into temporary HCF is considered an economical solution as opposed to constructing new facilities [30]. Facilities or spaces like schools, hotels, large halls are often converted into temporary HCFs to accommodate the increasing demand for healthcare even if it is for post-acute cases [30, 35]. For instance, in Canada, a multi-purpose sports complex in University of Alberta, has been turned into a temporary 100-bed facility [32]. In Singapore, an open-air car park of 3200 m^2 has been utilized to provide a temporary isolation ward extension [34]. Singapore Expo with an indoor space of 100,000 m^2 has been turned into a community care center with a capacity of 8000 beds to host non-acute COVID-19 cases [11]. In China, the Wuhan International Conference and Exhibition Centre and Hongshan Stadium were utilized to provide a joined capacity of 2600 beds (Wuhan Municipal Health Centre 2020). In Egypt, a temporary 4000-bed hospital field has been constructed in the Convention Center located in New Cairo. To decide about the most appropriate NMF for conversion, multiple aspects need to be considered, including: space, location, facility's internal design, area per bed, and conversion cost and duration. Due to the expected surge in number of cases, especially with the current second wave of COVID-19 virus and the new fast-spreading variant, public healthcare officials need to decide fast about the facilities to be converted into temporary HCFs to at least accommodate low-acute cases. To address this intricate decision-making problem and make an appropriate decision, OR/MS methodologies need to be deployed.

2 Disaster Management

Operation Research and Management Science (OR/MS) has been recently growing in importance for managing disasters [2]. Despite pandemics and outbreaks are considered disasters, yet most of the existing research efforts in the domain of disaster management are more concerned with humanitarian logistics and emergency responses in case of tornados, cyclones, hurricanes, etc. For instance, Balcik and Beamon [4] developed an optimization model to determine the optimum location for humanitarian relief distribution centers for quick response in case of disasters considering capacity and budget constraints. Dalal et al. [13] developed a model that groups villages into clusters in case of cyclone disaster and determines the optimum location and capacity of shelters that would serve those clusters in order to minimize the travelling distance, considering the available spaces. Jia et al. [22] developed an optimization model to determine the optimum location of emergency medical stocks to address the needs of large-scale emergency cases, considering the number of facilities, location, and the coverage service of each. Doerner et al. [14] developed an optimization model to determine the optimum location of public facilities (including schools) to reduce the risk of disastrous damages caused by Tsunami and similar natural disasters. Kongsomsaksakul et al. [25] developed an optimization model to determine the optimum shelter location for flood evacuation considering the time of evacuation and the routes to the shelters. Despite the existing efforts, there is lack of research that have utilized OR/MS to address the disastrous case of insufficient inpatient care during pandemics and outbreaks and how to provide swift response towards it. Accordingly, this research presents the framework of a comprehensive decision support system (DSS) that helps policy makers take proper and fast responsive decisions to confine unpleasant consequences of pandemics. It determines the optimum construction method and structural system in case of resorting to construction of new medical facilities, and optimum selection of NMFs that can be converted into temporary HCFs in a timely and cost-effective manner. The aim of this research is laying out the map for the proposed DSS to encourage governments to implement it to help take justifiable decisions and act swiftly to overcome shortage in healthcare capacity in a cost-effective and timely manner. The following section describes the framework of the proposed research and the adopted methodology.

3 Methodology of the Proposed Research

The framework of the proposed DSS, as shown in Fig. 1, consists of two main decision-making modules for provision of HCFs: (1) Construction of New medical facility, and (2) Conversion of NMFs into temporary HCFs. The first module helps determine the optimum structural system that satisfies the requirement of fast construction in a timely and cost-effective manner, and sustainable performance over time. In this module, an investigation of the potential structural systems and advanced

Fig. 1 Framework of the proposed research

construction methods will be carried out, considering construction materials, fabrication and construction procedures and sustainability. Afterwards, structural analysis and life cycle cost analysis will be conducted for the selected candidate structural systems, followed by a comparative analysis to come up with the most effective system. The second module determines the optimum selection of NMFs that can be converted into HCFs taking into account multiple aspects, including: the required time frame, capacity, location, technical and medical specifications, and available budget. To serve the proposed DSS in this research, there is a need for a comprehensive database about the existing HCFs in the city or area under study. The database should include the number of facilities serving the area, facility type (fully equipped hospital, mid-size medical center, etc.), geographical location, medical capabilities, capacity in terms of staff, ICU units, patient beds, etc. Moreover, information should be collected about the highly infected areas, and the expected number of severe COVID-19 positive cases that will need to be admitted to HCFs or post-acute cases that will need a close medical care. In addition, the potential occurrence of a surge in the number of cases as has been witnessed in the first and second waves of COVID-19 and its variant in some countries in Europe including United Kingdom. Such database is quite necessary in order to be able to identify and locate the shortage in healthcare capacity and identify the optimum location for the new medical facility. The following subsections describe each proposed module in further details.

3.1 Module 1: New Construction of Healthcare Facility

Design and construction of new health care facilities require the cooperation of several engineering and medical disciplines. There are numerous available structural systems which are generally classified according to construction materials, detailing, and fabrication and construction procedures. Selection of the optimum structural system is a challenging process that has to account for multiple parameters including availability of resources, functionality of the building, number of floors, in addition to several sustainability and environmental constraints [5, 15]. Proper selection basically depends on reducing the total cost of projects and time spent during the construction phase [6]. Generally, achieving the least possible cost is the target of any design team, however, requirements related to aesthetics, environmental impact, and construction speed pose a determining factor in many cases, in addition to medical requirements for HCFs. Common structural engineering practice relies on level of experience of the structural engineer to produce consistent, safe, and reliable designs. Many researchers have conducted comparative analyses among different structural systems to select the most suitable one for the case under study. For instance, Balali et al. [7] proposed a technique of multiple criteria decision-making to select the best structural system for low-rise multi-housing project. Turskis et al. [33] investigated the suitability of five possible structural solutions for a one-story building using a multi-criteria assessment method. Gasser and Schueller [17] applied the well-established reliability-based optimization techniques to decide on suitable structural systems based on total costs. Juhua et al. [23] combined building construction techniques and cultural conditions to build a decision-making model based on analytical hierarchy process method. Despite the existing research efforts, there is a lack of efforts addressing the decision-making problem to select the optimum structural facility that would allow fast and sustainable construction of HCFs in response to pandemic outbreaks. Accordingly, the aim of this module is to conduct comparative analysis to examine alternative potential structural systems for new build hospitals, considering shape of the structural skeleton, material availability, construction cost and time, associated construction method, and the expected life cycle costs. When dealing with construction of new HCF as a counter measure for increase in number of patients, construction speed represents a critical factor. Accordingly, the main objective is to determine the most suitable structural system that can be adopted for construction of HCF in the least possible time within the limited budget available.

The possible structural systems and construction materials are shown in Table 1

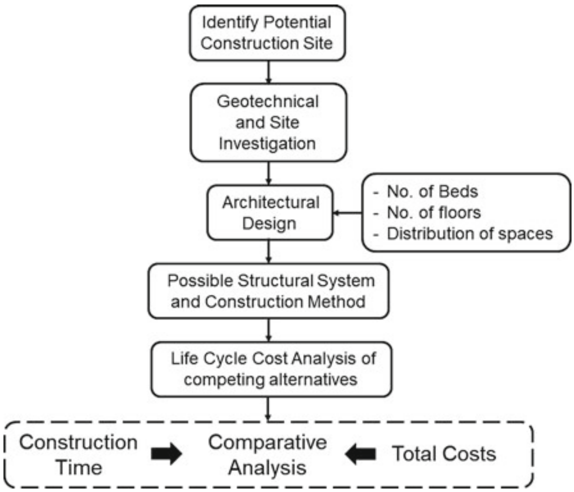
Table 1 Characteristics of potential structural systems for new build HCF

Competing structural systems	Construction method	Advantages	Disadvantages
Conventional RC skeleton	Cast in situ	Common, low cost, Fire resistance, acoustic and thermal insulation, high capacity, low maintenance	Heavy, long construction time
Steel moment resisting or braced frame	Assembly on site	Common, short construction time, sustainable material, robustness, and ductility	Costly, low fire resistance
Modular light steel building	Segmental construction	Lightweight, short construction time, sustainable material, robustness, and ductility	Costly, low fire resistance, shape constraints, only for low-rise buildings
Steel container modules	Segmental construction	Recycled shipping containers, easy transport	Additional reinforcing needed to strengthen container when openings are cut in walls
Precast concrete	Precast segmental construction	Fire resistance, acoustic and thermal insulation, high capacity	Costly, heavy, potential cracking at corners
Composite steel–concrete skeleton	Assembly on site + cast in situ	Fire resistance, acoustic and thermal insulation, high capacity	Heavy, long construction time, complex design and construction

along with the construction method, advantages, and disadvantages. Conventional reinforced concrete (RC) skeletons and steel moment resisting (SMRF), or steel braced (SBF) frames are considered as the most common structural systems specifically in Egypt and generally in the Middle East. RC system offers many advantages related to the low associated costs during construction and operation phases in addition to excellent performance in acoustic and thermal insulation. Despite that, RC is bulky, heavy and requires long construction time. SMRFs and SBFs are commonly used to cut down construction time and provide smaller sections considering the high strength-to-weight ratio of steel. However, they incur higher construction and operational costs. Composite steel–concrete skeletons take advantage of RC and steel merits but are generally complex to design and construct. Hence, longer construction periods are usually expected. To accelerate construction and provision of hospital beds, prefabricated modular units have been promoted in the construction industry [18, 35]. It significantly reduces construction time in addition to improved quality. These systems usually employ series manufacturing production line to divide supporting structures into light weight and series-producible modules. This can be applied to steel, precast concrete, aluminum, or timber modules. However, modular systems are usually suitable for low-rise buildings which are commonly used for public HCFs. For example, in Cardiff in United Kingdom, modular construction firm Darwin Group has been chosen to deliver a new £33 m COVID-19 hospital building to ensure capacity for patients in the event of a second spike in serious coronavirus cases [24].

Figure 2 illustrates the sequential steps of the proposed module to help select the optimum structural facility that would allow fast construction of HCFs in response to pandemics. First, several possible construction sites for a selected zone will be investigated. A potential site will be selected based on a set of criteria including

Fig. 2 Flowchart of the proposed module for new build HCFs



ease of construction, distance from city center, available nearby facilities, geotechnical conditions in the area as part of the decision-making module. For the selected site, a preliminary architectural design will be conducted following local standards, medical requirements and common practice for public HCFs (e.g., an average number of beds of 100 in hospitals in Egypt). A comparative analysis will be conducted to compare between the potential structural systems presented in Table 1. A detailed structural analysis and design will be performed for each candidate, to size the different members within the building skeleton. Afterwards, the cost and duration of construction will be estimated. Costs associated with the initial investigation of site, design, permits and approvals, site preparation, and foundations are common among all possible potential structural alternatives. Therefore, the analysis will only consider the costs that varies with the structural alternative being considered (e.g., material procurement, equipment and labour utilization, and construction method). In addition, life cycle cost analysis will be conducted to consider all costs over the expected life of the HCF that can vary according to the structural system.

Models for predicting accurate time and cost of construction projects were investigated by several researchers [12, 20, 28, 31]. Many efforts related construction time and cost to the general characteristics of the building such as number of floors, gross floor area, project type, contractor selection method, and contractual arrangement. However, there is a lack of efforts that have addressed the impact of different possible structural alternatives on the costs incurred. This will be accounted for in the comparative analysis following a detailed process for all involved work packages as part of the decision-making system. Construction and material costs will be based on building price index (BPI) in the price book [27] in addition to locally collected data for average rates. Afterwards, LCCA will be performed to evaluate each alternative economically over its service life, considering: costs related to installation, maintenance and operation of building envelope, mechanical and electrical system; and energy system, and any expected intervention costs required to preserve HCF condition and make up for expected deterioration throughout the service life. Budget limitations will be considered as an initial screening process to eliminate unfeasible alternatives. Once the economic worth of the total cost and construction time of the feasible structural alternatives are estimated, a multi-criteria analysis shall be conducted to further evaluate each competing alternative with respect to accommodation of medical requirements, ease of construction, and availability of material and skilled labor, etc. Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE method shall be adopted to perform the multi-criteria analysis [8]. Hence, the output of this phase will allow policy-makers to assess rigorously the construction decision of new HCFs to help justify the decision made.

3.2 Module 2: Conversion of NMF into Temporary Healthcare Facility

This module consists of an optimization model that helps determine the optimum selection of non-medical facilities to be converted into temporary HCFs, considering budget constraints, medical and logistic requirements, and required number of facilities per demand point where the shortage has been identified in the HCF database. Figure 3 presents a flowchart that depicts the procedure followed to develop this module, which starts by constructing a database of potential NMFs that are often facilities with large spaces (e.g., convention centers, hotels, sport complexes, stadiums, large schools, open-air parking areas, university campus). Once a pool of potential temporary HCFs has been populated, a screening process will be carried out to check the eligibility of each facility against mandatory medical criteria. Examples for those criteria include [9, 36]: safety issues, suitability of the internal layout for providing patient care, and accessibility to reliable power network, sewage and water utilities, and reliable transportation network. If the facility meets the minimum requirement of those criteria, it will be added to another pool of qualified candidate temporary HCFs.

For each qualified candidate, the cost and duration of conversion will be estimated, considering any alterations needed to meet any medical requirements. Since each

Fig. 3 Flowchart of the optimization module development process

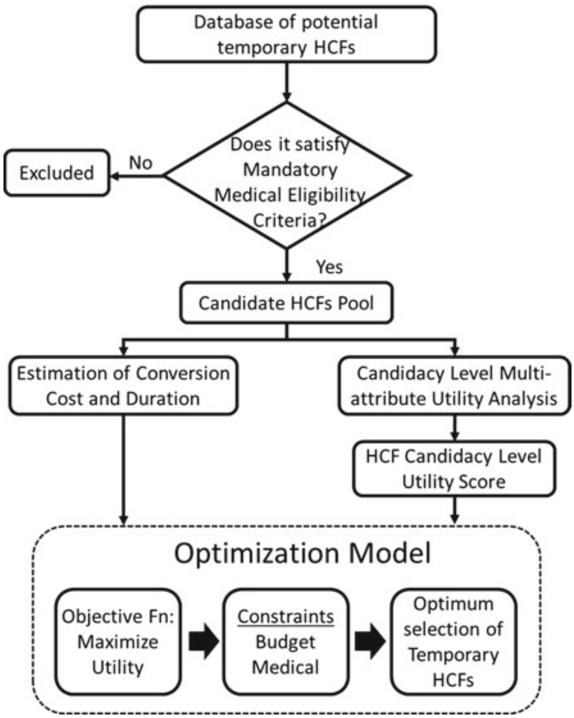


Table 2 Utility attributes of candidate non-medical facilities [3, 9]

Attribute	Description
Distance from city center	It measures the distance between the NMF and center of the city under study
Nearby hospitals (Number, Status, Proximity)	It measures the number of hospitals in the area where the NMF is located, and the distance between them. In addition, it identifies the status of those hospitals whether they are fully equipped hospitals or not
Logistical considerations	Neighborhood, traffic control, accessibility
Hygienic adequacy	It measures the level of hygiene in the NMF in terms of number of sinks, toilets, shower facilities, etc.
Spacing between patients	It measures the spacing between the patient beds in a given room or space beyond mandatory spacing between beds
Type of care	It determines the type of care that NMF could be used for after conversion (acute, mid-acute, and non-acute)
Storage area	Proper space for storing medications, cleaning tools, and waste

NMF has different features and characteristics, each one will be evaluated based on pre-defined attributes using multiple attribute utility analysis (MAUT), where an overall utility score is computed for each facility to represent the facility's level of candidacy. Table 2 summarizes the attributes that would contribute to the utility associated with the conversion of a given NMF into a HCF, yet they can be extended as per any future research. It can be noted from table that each attribute has a different measuring unit. In addition, some of them are quantitatively measured and others are qualitatively measured. Since each attribute has a different measuring unit, the value received by each facility w.r.t each attribute will be normalized to have the same numerical scale (e.g., 1 to 10). Each attribute will be assigned a weight to represent its importance and the decision makers' preference. Afterwards, a weighted utility score will be computed for each facility [19]. This utility score will be used later in the optimization model to represent the facility's priority when deciding among multiple facilities simultaneously and to compute the overall utility associated with the facilities that are selected for conversion, considering the budget available and medical requirements.

3.2.1 Mathematical Optimization Model

The goal of this optimization model, as previously mentioned, is to determine the optimum selection of non-medical facilities (NMFs) that can be converted into temporary HCFs to meet the required bed capacity. A linear integer-programming model with a single objective function of maximizing the overall utility associated with the conversion of those NMFs is used. The optimization parameters are as follows:

Decision Variable: a binary decision variable Y_i is used to represent whether a given facility *i* (*i* = *1, 2, 3… n facilities)* has been selected or not (if $Y_i = 1$, then the facility has been selected; if $Y_i = 0$, then the facility is not selected).

Objective function: is set to maximize the sum of the weighted utility scores u_i assigned to the facilities selected for conversion into temporary HCFs as formulated below.

$$\text{Maximize} Z = \sum_{i}^{N} u_i \times y_i \tag{1}$$

Constraints: total costs of conversion should be within the available budget stated by the concerned authority (e.g., Ministry of Health). The selected facilities should meet the medical constraints in terms of the bed capacity, duration of conversion, and time availability, as follows:

$$\sum_{i}^{N} (y_i \times C_i) \leq B \tag{2}$$

$$BC_L \leq \sum_{i}^{N} (y_i \times BC_i) \leq BC_U \tag{3}$$

$$y_i \times TA_i \geq TA_R \tag{4}$$

$$y_i \times DC_i \leq DC_R \tag{5}$$

where, C_i is the cost of converting facility *i* to a HCF, *B* is the available budget,BC_i is the bed capacity of facility *i*, BC_U and BC_L are the lower and upper limits for the required capacity, TA_i is the time availability after conversion (i.e., the duration where the facility can serve as a temporary HCF), TA_R is the minimum required time availability needed as a response to the pandemic surge (e.g., 4 to 6 months), DC_i is the duration of the conversion process, and DC_R is the maximum duration of conversion.

To implement the proposed DSS on a real-life case study, that would require quite a long time since there is a need for a comprehensive database regarding the current status of the existing Healthcare facilities and the non-medical facilities that have the potential to be converted into HCFs. However, currently data is being collected about a selected zone in Cairo as a test bed for the proposed research.

4 Summary and Concluding Remarks

The proposed research targets bridging the research gap related to emergency management during pandemic outbreaks. The main uniqueness point is combining and advancing previous analysis and management techniques to outbreak challenge that was not addressed before. Thus, the paper described the framework of a decision support system (DSS) which consists of two modules to help make reliable decisions regarding fast provision of HCFs. The first module's main objective is to determine the most suitable structural system that can be adopted for construction of new HCF in the least possible time within the limited budget available. While the second module's main objective is to determine the optimum selection of non-medical facilities for conversion into temporary HCFs, considering budget, medical and logistic constraints. Thus, the aim of the proposed study is to provide a reliable decision support system that can help policy makers take timely decisions to quickly accommodate the exponential increase in number of cases, and therefore confine its disastrous impact on the society and save hundreds of lives.

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A Case Study of the Impact of Modular Manufacturing on a Hospital Expansion Project

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1 Introduction

The adoption of information and communication technologies (ICTs) in construction projects accelerates access to information and facilitates communication among project stakeholders [10]. The integration of mobile technology is highly dependent on its accuracy and ease of use. In recent years, a significant improvement in workflows has been noted with mobile technology on construction sites [11]. New digital technologies allow access to a wealth of data that could potentially facilitate quicker key decisions. Various research studies have shown that the difficulty in accessing information quickly is one of the causes of significant productivity gaps in construction compared to other industries [18]. By adopting specific project management processes and using these technologies, contractors can improve their performance by reducing risk through upstream problem solving [18]. He pointed out that the disparities between the various players make relationships complex, while they need to exchange information and collaborate effectively. To try to improve the situation in the industry, several solutions are now available. These solutions imply a change in the processes within the construction teams. The process of integrating BIM and LEAN philosophies into the project promotes communication and information exchange. On the one hand, the many benefits of Lean practices have been highlighted in several studies. The use of Lean Construction strategies allows contractors to enjoy a wide

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range of benefits, including: superior construction quality, improved customer satisfaction, increased productivity and improved safety [4]. On the other hand, BIM improves communication, exchange and collaboration between the different project actors through a centralized database. These processes can bring great value, when used properly from the beginning of the design phase to the delivery of a construction project. BIM is a very powerful iterative and integrated design process, allowing the optimization of project performance throughout the entire life cycle [2]. With BIM technologies, each discipline generates schedules and analysis tools linked to a digital model [9]. The goal of working on the same collaborative platform is to improve the process of information exchange and problem solving. The greatest interest is to increase the potential for continuous optimization of the building. Lean and BIM are two very complementary processes [17]. In a study that demonstrated their innumerable interactions using a matrix juxtaposing BIM functionalities with prescribed Lean building principles, 56 interactions were identified, all but four representing constructive positive interactions.

The implementation of a project generally involves the awarding of service contracts to firms with skills in design, engineering, construction management, construction, financing, operation, etc. Several organizational schemes called "delivery mode" are possible. However, an analysis should be conducted for each project to identify the optimal procurement method that best meets the objectives. Furthermore, the construction approach (OSM, modular construction) and the appropriation of technologies (BIM, TMC, etc.) are of major importance both for the success of the project and for the satisfaction of the objectives. Hence the importance of the choice of the realization mode in the project's success.

2 The Integrated Design Process (IDP), BIM and Lean for Improved Performance on Site

According to Dionne [7] and Forgues et al. [8] the origin of the Integrated Design Process (IDP) is based on the principles of sustainable development, and aims at repairing human interventions that have altered ecosystems. IDP and its technological environment, BIM, is a design process that has just undergone a real revolution and whose impact on the construction industry is considerable. It allows for quicker and more accurate application of requirements and challenges at the design stage, in a sustainable development context. It allows for improved productivity [15] in the field, reduced changes and therefore reduced conflicts [1]. It yields improved field productivity, predictability, and reduced costs and construction time. These features allow for the reduction of waste and definitely add value to the client.

3 OSM and Modular Construction

The adoption of modular construction in new real estate projects in North America increased by 50% between 2015 and 2018 [13]. Efficiency is an inherent characteristic of modular construction, which offers great potential for it to be a desirable strategy for rapid, quality construction. The many advantages of modular construction favor its adoption for short time frames such as post-disaster reconstruction. Despite the many advantages offered by OSM, this market is still small and under-exploited by architects and developers. According to a study conducted by Mortenson Company [14] during the construction of Denver's new 831,000 square foot hospital, prefabrication helped reduce the schedule by 18%. The study showed a benefit-to-cost ratio of 1.13 for every dollar spent on prefabrication, about 13% of the investment, was returned as a quantifiable benefit to the project [20]. A study by the University of California, Berkeley, found that samples of Permanent Modular Construction (PMC) projects were 11% more cost effective and 42% better than traditional site-built projects. In addition, the use of standard modular units not only facilitates site-controlled fabrication and on-site assembly, but also further consolidates the design phase [3]. Modular construction increases the predictability of planning during both fabrication and assembly. Nevertheless, educating the construction industry on the use of BIM is necessary for the successful implementation of off-site prefabrication [16].

Prefabrication of subassemblies in MEP systems allows contractors to improve their bid by reducing construction schedules and critical construction issues. It is the solution that allows the assembly to be created in a more efficient manner, minimizing the actual installation time, while reducing errors and difficulties on site. The level of feasibility of prefabrication differs between MEP systems, connection methods and project types [12]. So, firstly, the challenges and barriers of prefabrication must be identified, and secondly, clients must be convinced to take this unexplored route, as it can often be more costly at first, and fraught with uncertainty for them. In the construction industry, *Design for Manufacturing and Assembly* (DfMA) is already being used and if it follows the same trend as the manufacturing industry, it could easily become the norm in a short time [21]. Literature has already shown that OSC can be advantageous in terms of cost and reduction of construction time [5].

4 Methodology

In order to study the impact of the modular approach and OSM on the realization mode, we proceeded with a case study. The case study is a research approach used to generate an in-depth and multidimensional understanding of a complex problem in its real context [6]. This research model is widely used in a variety of disciplines. A lack of case studies involving the adoption of the modular approach with OSM and the integration of new technologies to improve the productivity of MEP contractors in a construction project supports the relevance of this case study. The first stage involves

Table 1 Function, role and identification of project stakeholders interviewed

Role in the project	Function	Identifier (ID)
Customer	Project Manager	CL
Client's project manager	Project Manager	GDP
Construction Manager	VP Construction	GCVP
Specialized MEP contractor	Director of Mechanics	ESDM
Specialized MEP contractor	Sales Manager	ESDV
Specialized MEP contractor	Head draftsmen	ESDT
Architectural firm	Architect	ART
Consulting engineering firm	Mechanical engineer	ING
Manufacturer of modular units	President	BPF

the study of current practices, identification of challenges in adopting OSM, MEP contractors' attitude towards prefabrication through a comprehensive data collection process, including site visits (of a project adopting modular OSM and integration of new technologies) and semi-structured interviews with project stakeholders. The second step involves data processing and analysis to highlight important information about the practice of OSM. The third step consists of formulating suggestions as to the path to follow by the different actors in order to make a successful prefabrication project. The main actors in this project were interviewed. Table 1 summarizes their function as a stakeholder, the position in the project and an identifier for each stakeholder.

5 Description of the Case Study

The HMR-Modular project involves the construction of a two-storey modular building with a crawl space of 1600 m^2 per floor. Part of the building will have a basement to access the tunnel that will connect the new building to the existing hospital. The building illustrated in Fig. 1 consists of work spaces (reception, professional stations, nurses' stations) and isolation rooms; constructed of juxtaposed metal modules, equipped with a vestibule acting as an airlock, a non-contact hand-washing station and a washroom including an adapted shower. Each of the 36 rooms is equipped with a controlled pressure system according to use (positive pressure for oncology patients and negative pressure for patients with contagious diseases).

Fig. 1 The Maisonneuve-Rosemont Hospital expansion project

6 Presentation of Results

The main drivers for the choice of modular construction were the timely completion of the project while ensuring a high quality construction. The decision to go ahead with a modular construction was quickly made by the client's representative. This decision naturally greatly influenced subsequent decisions related to the project. Figure 2 illustrates the contractual process and the links between the players in this project.

According to the stakeholders, the construction management realization mode helped establish an atmosphere conducive to collaboration as well as the implementation of digital solutions to facilitate the project conduct. In this regard, during multiple site visits we noticed an atmosphere of collaboration and information sharing

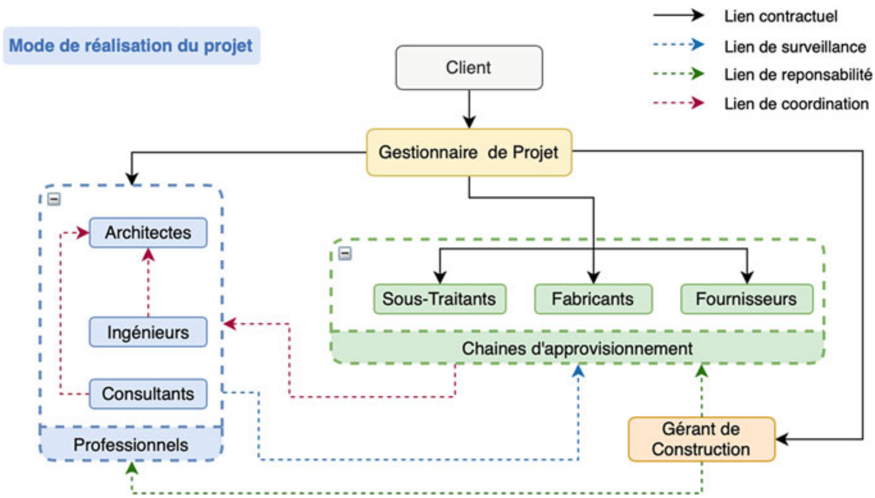

Fig. 2 Contractual process for project delivery (construction management)

between the managers and employees of subcontractors. According to the architects, they succeeded in ensuring a better involvement of the client in the design process of this project. On the other hand, it should be noted that we did not notice an application of Lean principles in the logistic organization of the construction site. The implementation of Lean principles in this project would certainly have increased productivity and eliminated waste.

At the same time, according to our observations, interviews and documents to which we had access, the use of CMTs in this construction project, such as the platform for sharing documents and for tracking deficiencies, made it possible to improve communication and increase the productivity of the actors in the project. The positive impact of TMCs was emphasized by most stakeholders. The use of these collaborative and centralized platforms ensured the sharing of models and digital information and led to successful communications between stakeholders. However, the use of BIM was not a contractual obligation in the project. Despite this fact, the electromechanical contractor proceeded with the modeling of the MEP systems. The architect and the structural engineer each modeled their building discipline using Revit. Their 3D models were used by the electro-mechanical contractor's engineer who modeled the HVAC systems in addition to performing interdisciplinary coordination. According to the testimonies of some of the actors, the use of BIM has made a very positive contribution to this project, both in the prefabrication of MEP subassemblies and in the connection of the HVAC systems between the modular units.

6.1 Impact on the Timeline

As mentioned, the choice of modular construction was made to reduce the overall project schedule by more than 50%. The benefits of this accelerated construction mode, especially in the context of critical asset delivery, are considerable. Following the experience during the project, the client stated his overall satisfaction with the involvement of the engineers, architects and contractors in the construction process. He stated that the most appreciated advantage of modular construction was in terms of the speed of execution of the construction work.

In order to meet the project deadline, the MEP systems are assembled in the factory, then installed and connected on site. Visits to the construction site provided an opportunity to observe the processes, as can be seen in the photos of the prefabricated assemblies (Fig. 3). The left side of the figure shows 40-foot long assemblies before

Fig. 3 Factory-assembled and on site installed MEP systems

Fig. 4 Modular units and the challenges of fitting them into the building

they are delivered to the site. The right side of Fig. 3 shows these MEP system assemblies after they are installed on site. With these multiple assemblies filling the ceiling spaces, one can see in these photos the difficulties that could have been caused by installing these systems in a traditional manner.

Modular construction has been found to be limited by two major logistical challenges: handling and transportation. Handling is limited by crane capacity, while transportation is limited by truck restrictions and dimensions. The intensive heavy lifting operations involved in construction and assembly are major technical handling challenges on site. These operations are meticulous and require a high degree of planning and expertise. Therefore, it is important to bring the companies' deep experience in shipping and logistics to facilitate the appropriation of modular construction in projects. On the right and center of Fig. 4 we can observe the operations of insertion of modular units in the structure of the building, while on the left of the figure we can see the modular units during the manufacturing process in the factory. When the modular unit leaves the factory, it is ready to be used, just needs to be connected to the services.

In this project, the work is done in parallel at the factory and on the construction site, which not only reduces the number of employees at the construction site, but also the risk of accidents. This reduction in the number of workers on the construction site reduces traffic on site and improves the productivity of the teams. The reduction of the number of employees on the HMR-modular construction site has allowed to improve considerably the productivity especially for the respect of the sanitary instructions and distancing on the construction site. In addition to improving productivity, downsizing has improved safety and reduced the number of accidents and associated costs to contractors. No major accidents were reported during the execution of this project.

6.2 Impact on Productivity

It should be noted that in this project, many of the benefits and positive impacts on productivity came from the fact that the MEP disciplines were under the responsibility of the same company. However, the manufacturer of the modular units developed the skills within their company to respond quickly to the needs of the client. The teams worked tirelessly to create a first prototype, then ensured the production of thirty-five rooms for five months, while the civil and structural work on the site was carried out.

Although BIM was used in this project for the development of the concept and the documentation as well as for interdisciplinary coordination, some difficulties were encountered, particularly in optimizing the flow of information within the project team. The centralized database, fed and shared by all stakeholders, is the key to the benefits from BIM in this project. The project was modeled by the design team at the architectural and structural levels, and mainly by the electromechanical contractor as far as the MEP systems are concerned. The electromechanical contractor took full advantage of the use of BIM for off-site prefabrication, installation and assembly of the modules on site. However, the modular unit manufacturer could not fully benefit from the digital models produced by the architect, structural engineer and electromechanical contractor, due to lack of access to the appropriate software and low BIM maturity. Among other things, certain parts of the modular units were not modeled as manufactured for insertion in the design model, which did not allow the team to carry out detailed coordination. In addition, there were interoperability problems between the design software and the production tools.

6.3 Impact on Cost

Stakeholders' opinions are divided on the notion of project cost and the gains made through OSM, as illustrated in Table 2. Some felt that the project costs more than a conventional project, while others did not see a large cost difference associated with OSM and the modular process. Rather, they associated additional costs with the acceleration of the work and the higher quality of the project deliverable. Based on our observations, it is important to mention that the number of issues (deficiencies) was considerably low compared to other projects of the same scope, less than two hundred deficiencies of which more than 95% are minor ones.

Compared to the traditional method, the interviewed stakeholders noticed that OSM is a better solution that allowed for process improvement and quality control of the design. On the other hand, they had to invest more effort in it compared to conventional projects in terms of coordination. Moreover, the consultants were in constant communication with the manufacturer of the modular units, as they lacked experience in terms of quality control of the design of modular units.

According to the construction manager, the project delivery costs were higher than a similar project in a conventional construction mode, due to the development and engineering services, as well as the fast-track mode required by the client. In addition, the construction manager faced some difficulties in synchronizing the traditional construction activities like the lifting, positioning and installation of the modular units into the building structure. These problems were caused by insufficient use of technology, namely incomplete BIM coordination and lack of 4D simulation. On the other hand, the constructor was able to accelerate the project and improve the management of activities on the site, all of which resulted in better quality and durability of the construction.

Table 2 Impacts of OSM

ID	Impact of OSM on the timeline	Impact of OSM on productivity	Impact of OSM on project costs
CL	Reduces the time frame		It's the same costs
GDP	OSM should be part of the design whenever the timeline is shortened	It is a first experience, subject to improvement with the learning	In the factory, there are savings in labour costs, since there are no union dues to pay
GCVP	Allows the reduction of the schedule	Yes, it improves the productivity of everyone involved	The OSM is of a higher quality, does not necessarily cost less. The gains are in the acceleration of the work
ESDM	Significantly reduces the time frame	The importance of the performance and profitability of prefabrication in the factory, which accelerates the pace of construction and increases the productivity of all participants	There are costs that have been saved, but there is an additional cost due to the construction approach. The manufacturing cost is lower in the factory
ESDV	Reduction of the timeframe	Improves the productivity of all disciplines	The gains on manufacturing in the factory will pay for the transportation and handling by cranes at the construction site. This is difficult to quantify in order to compare the gains in labour between OSM and the traditional mode
ESDT	Shortening the schedule by half	It is very productive that all disciplines are under the responsibility of the same MEP contractor for all actors. It avoids the mobilization of each one to wait for the other to finish his activities	The more time you spend on the drawing board, the less time you need on the job site. Less time and resources on the job site reduces costs significantly
ART	A reduction in the project timeline	It's productive, over time it improves productivity, but it takes time to learn	Yes, the costs are significantly affected by OSM
ING	Significantly reduces the time frame	It takes a period of adjustment to improve productivity (learning curve)	It is certain that there is a reduction in project costs

(continued)

Table 2 (continued)

ID	Impact of OSM on the timeline	Impact of OSM on productivity	Impact of OSM on project costs
BPF	The project cannot be completed in time without the OSM	It improves productivity, because the work in the factory is safer and does not depend on the weather conditions. So, better conditions	Factory manufacturing allows the use of technology and automation to reduce production costs

7 Discussion

Designer interaction in the virtual environment fosters a highly creative experience and enhances understanding of complex scientific concepts [19]. Users can best achieve their self-improvement goals by using technologies that include functionality. As technology users, setting goals focused on competitiveness can drive them to improve performance and personal growth, but focusing goals on cooperation is preferable for increasing behavioral engagement and life satisfaction [22]. However, involving stakeholders early in the design phase of a project ensures ownership of the project and presents an opportunity for satisfaction, as the multiple qualifications of the group allow for quick solutions and problem solving despite their complexities. In this project we observed a great satisfaction of the client by his involvement in the design phase.

In this project, the modular approach pushed the project team to exchange quickly and frequently. The construction management realization mode, and the fact that the manufacturer was involved from the beginning, were key to the success of the project. Design coordination, i.e. communication between the architects, engineers, electro-mechanical subcontractor, modular unit manufacturer and other suppliers, intensified during the project. The use of BIM facilitated this communication. This had a positive impact on the quality of the design and the speed of execution by the electromechanical contractor.

The climate of mutual aid and trust between contractors has had a positive impact on their productivity. The loss of productivity is a source of conflict between stakeholders and a subject of complaints in most construction projects. Modular construction has made it possible to reduce the number of workers on the site in order to respect the public health instructions of physical distance from the site. Under these particular conditions, the schedule could not have been achieved without the adoption of the modular approach and the OSM.

8 Conclusion

The contribution of this research project to the body of knowledge is twofold. Firstly, it has highlighted the difficulties the construction industry faces in assessing the performance of OSM adoption and the correlation of the results with this construction method. Yet, there is compelling evidence that the adoption of OSM is beneficial to the industry. However, traditionally, the project stakeholders do not automatically consider its integration into their projects. This case study is further evidence that the adoption of OSM is highly beneficial to all stakeholders. Secondly, this project has demonstrated how collaboration has enabled stakeholders to innovate. It also revealed the importance of using technologies such as BIM for the success of OSM. This project identified the numerous benefits of OSM, such as speed of project delivery, improved quality of deliverables, site work limited only to the inter-modular connections, efficiency and improved productivity of MEP contractors, and cost reduction through factory production at lower cost than on site. In addition, OSM is a methodological process that ensures repeatability and rapid replacement of components, thus reducing waste. OSM considerably reduces the amount of work on site, as well as the amount of manual work. The specifications and materials used are the same as those of on-site construction, while production and performance are better in a project adopting OSM. Therefore, OSM may be a solution to the significant shortage of skilled workers in many disciplines of the industry.

In conclusion, according to the literature and the results of this study, a construction management realization mode in combination with the use of BIM and the adoption of the modular OSM approach would offer the construction industry a new collaborative paradigm that encourages the sharing of information and profits, while ensuring an optimal result of the product delivered to the owner. The combination of these approaches not only reduces production costs, but also the occupancy rate on the construction site, while minimizing delays and maintaining a high final quality of the deliverables. IPD procurement and the integration of Lean processes would probably have yielded even more beneficial results.

There is a need to continue this research project in order to find a methodology to quantify the benefits of OSM for industry professionals, as well as for those who influence decision making for construction projects, including clients, consultants, financial institutions and policy makers. Such future research could result in a guide that supports decision-making on policies and criteria for the adoption of OSM in projects.

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Why Do Energy Projects Fail? Understanding How Controversy Impacts Construction Projects

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1 Introduction

The successful implementation of energy projects worldwide is critical to ensure global energy demands can be met. In accordance with global policies (e.g. Paris Agreement and Sustainable Development Goals, [35]), there is a need for investments in clean energy sources [24]. Despite government support in many countries, such as funding in the United States and European Union [11, 26], renewable energy projects often face public controversy throughout their project lifecycle. Wind energy projects, in particular, have encountered opposition from community members for a myriad of reasons, including noise disturbances [29], landscape aesthetics [9, 25] and wildlife protection [6]. Controversy has also taken various forms, such as community coalition groups, lawsuits [27], or public demonstrations [17]. Literature lends little insight into how energy developers can anticipate which actors will lead such opposition, what form this opposition will take, and how to plan for mitigation of potential cost and schedule implications. There is not a known standard method across the industry for dealing with these challenges. Moreover, there is little literature for project developers

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to reference to understand best practices for engaging with opposing stakeholders [27], existing literature primarily focuses on internal project conflicts causing delays [16, 18]. For example, there has been significant research on estimating the costs of delays due to labor issues, supply chain logistics, and rework [23, 32]. Other studies focus on issues concerning incomplete designs and the benefits of collaboration between designers and builders early in the conceptual and design phases [27].

It is important to recognize the impact of external stakeholders on construction projects, as they can cause delays and unexpected costs throughout planning and construction. Infrastructure projects broadly—of which energy projects are of interest to this study—are sociotechnical systems including both human and technical components that cannot be decoupled [3]. For instance, wind energy development relies on a skilled workforce to manufacture, install, and operate equipment. In turn, communities rely on the energy project to power their homes and businesses. The sociotechnical nature of energy projects–and infrastructure projects in general—is the reason controversies are likely to arise, as community actors challenge the benefits and project features that are defined and promoted by developers [7, 28]. We posit that we can capture this interdependency between social and technical systems by exploring and analyzing controversial projects across time and place. Through this analysis, we can find the common issues causing misalignments between industry and local stakeholders and highlight solutions that can lead to recommendations for best practices in the future.

Here, we aim to explore public controversy in historic wind energy projects through a media analysis and subsequent qualitative coding of news articles deemed relevant to our study. We systematically identify the (1) types of stakeholders involved in controversy, (2) actions taken by stakeholders, (3) project phases during which conflict occurs, (4) arenas where the controversy takes place, (5) consequences of the controversy, and (6) responses by energy companies. The media analysis enabled the collection of information across a large number of construction projects to see overall trends emerging in the construction industry, departing from most literature that relies on a small subset of case studies [23, 27]. This information allows us to draw conclusions about why controversy may occur in wind energy projects, who the responsible stakeholders are, and which stages of the project are most vulnerable to controversy, further, we make practical recommendations for energy companies worldwide on how to better engage with local stakeholders.

2 Methods

We performed a content analysis (i.e. systematically classified communication content based on categories; [2]) of media data using the Nexis Uni database to collect news articles concerning wind energy projects globally [21]. Analyzing media enables us to capture discourse and reflect upon how society engages with this subject. Researchers have noted that content analysis of mass media is “an indirect way of making inferences about people” [2]. In turn, by capturing discourse occurring in the

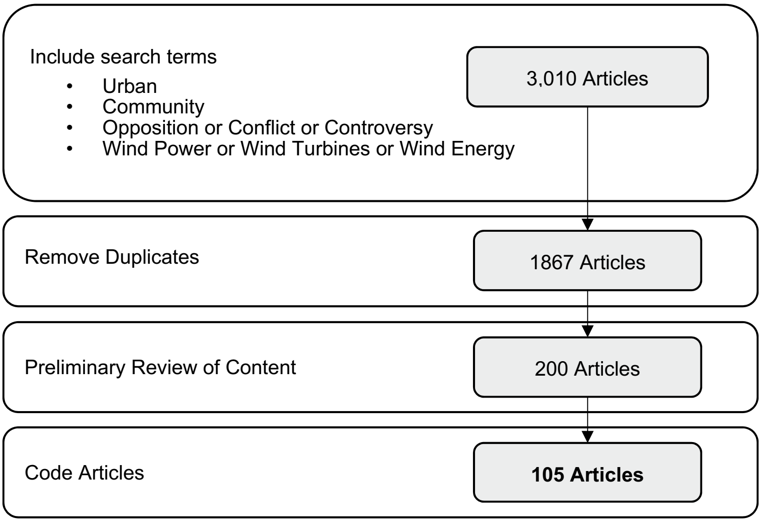

Fig. 1 Media search process

media, we are able to better understand perspectives of stakeholders during controversy in multiple construction projects and project phases. Figure 1 summarizes the media analysis process. The initial media article selection included a broad search of specific active keywords related to controversy in wind energy projects. After eliminating duplicate and off-topic articles from the initial search, we narrowed the search from 3010 to 105 relevant news articles representing a range of projects, geographic locations, and controversies.

We conducted a qualitative analysis of the news articles to identify emergent themes using NVivo Data Analysis Software [31]. We began first with deductive coding, where a list of codes is determined prior to analysis [8], using a framework seeking the (1) rationale, (2) action, and (3) context describing the conflicts surrounding energy projects. This framework was co-designed with academics and subject matter experts working in an international energy organization. We then applied an inductive coding process, allowing further sub-codes to emerge that described the details of the controversies which constituted the core of our coding dictionary. These sub-codes included specific stakeholder groups (e.g. community members or political leaders), oppositions/reactions (e.g. public demonstration or a letter to the editor), and project phases in which the controversy occurred, amongst other themes or project characteristics that emerged in the data (Table 1). For the purposes of this study, we broadly defined five phases of a typical energy construction project: proposal, preconstruction, construction, operation, and decommissioning (Table 2).

We used code co-occurrence to identify which stakeholders were most active during the different phases of a project. For instance, community members were most active during the proposal phase, followed by federal government agencies and

Table 1 Coding dictionary

Code	Definition
Rationale	
Stakeholder	The people or organizations involved in the project controversy
Motivation	The reason for opposing the project
Jurisdiction	Position of power or authority
Action	
Opposition	The action taken by those who are trying to stop or change the project
Reaction	The action taken by the entity trying to implement the project, as a reaction to an opposing action
Consequence	The impact of controversy on the project
Context	
Project phase	The construction project phase in which the conflict takes place
Geographic location	The country in which the project is planned/built
Opposition arena	The location in which the opposing action takes place
Reaction arena	The location in which the reaction takes place

Table 2 Definitions of the five phases of an energy construction project and coding frequencies

Project phase	Frequency	Definition
Proposal (prop.)	178	The project is sited, designed, and approved by authorities
Preconstruction (precon.)	16	Material is manufactured offsite and the site is prepared for construction
Construction (const.)	7	Turbines are brought to the project site and installed
Operation (ops.)	23	Wind turbines are operational
Decommissioning (decom.)	2	The wind turbines are shut down, disassembled, and removed from site

local organizations. The co-occurrences also revealed that community members were most likely to participate in interviews with news media or provide public comments as a form of opposition.

As with any study, our study is not without limitations. Because we are using media data as a source, controversy that occurred through media (e.g. opinion pieces in newspapers) may be overrepresented in the results compared to other arenas (e.g. social media). Additionally, media may be biased. Media outlets may choose to present the views of specific stakeholders (e.g. residents) over those of other stakeholders (e.g. energy developers), and the level of attention given to certain controversies and involved stakeholders may not reflect their true significance as measured by project impact. However, as other researchers have displayed, insightful conclusions using media data can be made [4]. In fact, media provides unique insight about the social systems that cannot easily be inferred from other data sources (e.g. project reports).

3 Results

We identified the project attributes that were most frequently discussed in news articles (Tables 2 and 3). The articles focused overwhelmingly on controversy occurring in the proposal phase of the project (79% of phase excerpts).

Of the stakeholders, which were divided into categories according to geographic reach and function, community members were the most active group (34% of stakeholder excerpts). Government entities, ranging from local to national, appeared in 26% of the coded stakeholder excerpts. There were also various stakeholders categorized as "other" due to the small frequency at which they occurred in the media sources. These included celebrities, religious leaders, design professionals, and indigenous groups.

Table 3 Frequency table showing codes for each project phase

Project phase	Prop	Precon	Const	Ops	Decom	Unspecified
Opposition						
Activism	20	1	2	0	0	1
Legal, governmental action	41	4	1	6	0	0
Share information publicly	66	7	3	8	0	10
Other	41	3	2	8	1	17
Reaction						
Continue project	17	6	1	1	0	0
Engage with community	9	0	0	1	0	0
Legal, governmental action	12	0	1	0	0	1
Make changes to project	13	3	0	2	1	4
Share information publicly	11	1	0	0	0	0
Withdraw, terminate project	7	0	0	1	1	0
Stakeholder						
Community members	95	11	4	10	1	13
Local council, government	41	2	0	0	0	6
Local organization	33	1	2	4	0	6
National government	28	6	0	5	1	4
National organization	13	3	0	1	0	1
Private corporation	48	1	3	7	2	2
State, provincial government	10	0	0	0	0	0
Other	19	0	2	5	0	5

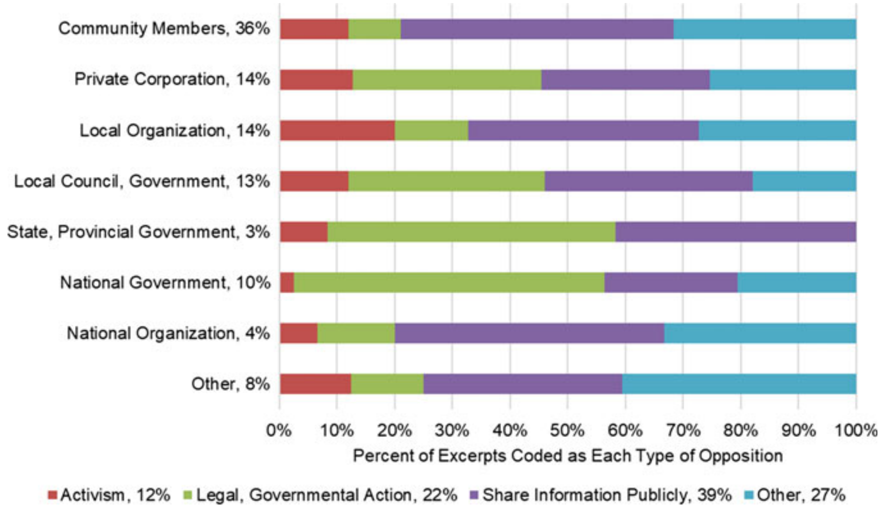

Fig. 2 Form of opposition by stakeholder group

The actions taken by the stakeholders in opposition were divided into four broad categories (shown in Fig. 2), (1) activism (e.g. petition, public demonstration), (2) legal/governmental action (e.g. local council decision, lawsuit), (3) sharing of information publicly (e.g. interview with media, letter to the editor), and (4) other (e.g. proposing an alternative design, conducting research, social conflict). Notably, 39% of all opposition was coded to "share information publicly." This action was even more prevalent among community members, with 47% of their actions coded to this category.

4 Discussion

4.1 Project Phases

The media analysis revealed that most of the discussion around energy project controversy in the news occurs during the proposal phase. This is actually ideal for energy developers (if controversy does occur) because the cost implications are less significant during this phase; it is also the easiest to make modifications to the project. Developers could, for instance, engage with stakeholders during the proposal phase to learn about their motivations for opposing the project (e.g. environmental concerns, noise disturbances) and work to mitigate these issues with minimal impact to the project. For many projects, there are required community engagement activities during the proposal phase per local, regional, or national regulations, including public meetings or commenting periods [20]. For instance, in 2010 in Ashfield, MA, an energy developer held a meeting in town hall to share information on a proposed wind development where many residents attended to express their opposition [34]. The developer engaged with community members to understand and address their concerns about the project. In 2003 in Newcastle, UK, the local council received over 1000 letters from local residents expressing their support or opposition for a proposed wind project [34]. The council was expected to review the feedback from the community, with 60% opposing, and consider this in their approval decision. Due to the nature of news articles, we do not know how these concerns were—if at all—addressed at a later date.

It is important to note that the potential impacts of a schedule delay in each project phase differ based on work performed and investment already committed to the project [22]. Conflict occurring during the proposal phase likely will not have as significant cost implications compared to subsequent phases. In the proposal phase, material has not yet been purchased, permits have not been secured, and workers have not yet been contracted [13]. As the project moves into the preconstruction phase, the cost of delay increases because of material procurement and land purchases or leases. For a wind energy project, this phase is especially significant because of the high cost of manufacturing wind turbines [36]. Once the turbines are manufactured and the project site is prepared, the construction can begin. The construction phase for a commercial wind farm is fairly short because the wind turbine components are manufactured offsite and simply assembled onsite [12]. However, delays due to opposition can cost the project a large sum for storage of the wind turbine component parts, land leasing, and loss of revenue. Once the turbines are installed and operation begins, any shutdowns would lead to revenue loss. The decommissioning phase, not explored in great detail in this study, will have different implications because this phase includes ending operation and removing the turbines.

4.2 Stakeholders

Analysis revealed that community members are the stakeholders most often mentioned in news articles regarding project controversy. These community members include residents who live near the planned project site [14, 20], environmental activists concerned about the impacts of development [15, 29, 30], and local business owners worried about the implications of industrialization [10, 19]. Community members often take action against projects by engaging media sources and by attending public meetings. It is important to note that this finding may be tied to our data source, exemplifying media as a common medium. These stakeholders commonly discuss the potential impacts to their lives if the wind turbines are built–noise disturbances, loss of property value, destruction of visual beauty. Developers can engage these community members by presenting information, through news media or public meetings that supports the advantages of implementing the project. They can also ease residents’ concerns by showing the project benefits to the environment and economy. Nonetheless, while developers can mitigate controversy through this avenue, engaging with community members is unlikely to have a significant impact in preventing schedule delays and cost overruns. Engaging with landowners, on the other hand, may greatly affect project success. Because on-shore wind turbines are often sited in rural communities, they require vast spaces of land for construction and operation. Many wind development companies work with local landowners to lease the land needed for the turbines. Engaging these residents early in the proposal process and offering fair monetary compensation can help mitigate potential schedule delays during permitting and construction.

Although community members were the stakeholder most frequently discussed in the news media, it is important to note that they are often not the most influential. Rural residents, in particular are frequently unable to create enough controversy for the developers to react and take any form of action. In Kern County, California, community members recognized this, stating, “we don’t have any voting power because we’re not packed into a square acre” [6]. This demonstrates that it is unlikely that community engagement alone will have any significant impact on preventing project delays or cost overruns. Political leaders, on the other hand, often have decision-making power in siting approvals and permitting, and thus, might be able to more directly influence a project outcome. In San Bernardino County, California, the Board of Supervisors voted to ban wind development in many rural communities, a decision motivated in part due to rural constituents’ opposition [33]. Particularly at the local level, political leaders are heavily influenced by the community members they represent when it comes to development decisions. Notably, political leaders’ involvement in energy development projects will be influenced by political forces, such as election schedules. In determining who to engage with at the onset of a project, developers can likely be more effective by engaging with political leaders as well as community members. Through lobbying or presenting at local council meetings, wind energy developers can share accurate information regarding the benefits of wind energy projects. In engaging with both the impacted community and the appropriate decision makers, developers may be able to mitigate the effects of schedule delays or cost impacts on their projects.

4.3 Media’s Role in the Opposition

Community members who are opposed to a wind development will often work together to garner support from other residents and political leaders. They can be rather effective by sharing their experiences, scientific research, and stories of other communities through various outlets (e.g. letters to the editor, social media posts, media interviews). In many communities, residents form coalitions and host events where community members can learn about the potential impacts of wind energy development. Through these actions, they hope to build opposition in the community and influence political leaders to use their power to stop the development. In some communities, groups will establish public demonstrations to try to directly influence the energy developers. For instance, in Ontario, Canada, Port Elgin residents planned to form a picket line at a wind turbine construction site to demonstrate their opposition to the project [1]. As many energy companies try to preserve their public reputation, this type of action can be effective in at least delaying a project.

Our analysis revealed the unique impact media has on controversy in construction projects–media was often used simultaneously by opposing stakeholders and by developers to garner support. This theme is especially evident when looking at the case of a wind project in Maribyrnong, a suburb of Melbourne, Australia [5]. Much opposition, including community organizing through information sharing, was conducted through media. Many news articles included direct quotes from residents. For instance, one resident was quoted saying, "It would be an eyesore," and further explained that the turbines would impede on the natural beauty of the community. This communication likely influenced other community members to oppose the project. On the other hand, the Maribyrnong Mayor used the media to explain in a local news article that the wind project was an important step in the community's mission to become carbon–neutral. By sharing this information, he hoped to "help our communities understand our environmental responsibility" [5]. Energy developers can learn from this community's example by increasing their own engagement with media outlets. By using media to share factual project information, developers can provide education to the general public who may be concerned about the impending project.

4.4 Supporters' Reactions

The actions taken by those supporting the projects follow a similar pattern to those in opposition. Most of the reactions coded in this study take place during the proposal phase of a project. This is important to recognize because developers can engage with opponents during this phase to prevent conflict and delays in subsequent phases. Notably, the action taken by the supporters most often is to simply continue with the project. Depending on the stakeholders, this might include approving a project (local councils) or simply ignoring the opposition (private corporations). This is a valid reaction as many opposition efforts may not be impactful enough to cause significant schedule delays for the project. Developers may determine that the most effective tactic to reduce their risk is to avoid engagement with stakeholders altogether. For instance, community members fought a transmission line project in South California in 2010 that would bring solar and wind power from rural areas to urban centers. While many opponents claimed that the project would not be economically feasible, the developers proceeded with the project. More than 10 years later, the project is fully operational and bringing clean energy to Southern California residents [29].

5 Implications

This study indicated that developers could benefit from engaging with opposing stakeholders during the proposal phase of a project, minimizing the effects of schedule delays and cost overruns. Delays or design changes during this phase are the least costly due primarily to the lack of investment in physical material at this stage. Developers could potentially minimize opposition during subsequent phases by engaging stakeholders through education (possibly through media) or even making changes to the project design. By working with stakeholders in this first phase, developers may be able to placate their concerns so that by the time construction begins, those stakeholders will be less likely to actively oppose the project. Recognizing that local political leaders represent community members, engagement with both types of stakeholders can be beneficial. While community members may be impacted the most by a new development project, political leaders have far more decision-making power to influence the implementation of a project. It is most effective to communicate with stakeholders through outlets that are easily accessible to them, including news articles and public meetings. By doing so, developers can demonstrate that the information they are providing is factual and transparent, building trust between all stakeholders involved. Ultimately, developers will need to perform their own cost/benefit analysis to determine whether engagement will be effective in limiting the cost of controversy, or so expensive that the cost of engagement is not worthwhile.

6 Conclusion

Clean energy is essential to sustainable growth worldwide. However, many energy development projects provoke controversy in the communities in which the project is planned. Here we analyzed 105 news articles that discussed the conflicts surrounding wind energy construction projects. We performed a content analysis on these news articles to understand the stakeholders involved in the controversy, types of controversy, where the controversy occurred, consequences of the controversy, and responses taken by developers due to the controversy. We found that conflict most often occurs during the proposal phase of a project. As such, energy developers should engage with opposing stakeholders at this phase, when costs of delay and redesign are low. While community members are the stakeholders most often discussed in news articles, it is actually the political leaders who likely hold the most power in opposing an energy project. Notably, these political leaders may be spurred by community organizing or public communication. This is often done through media, likely in an effort to sway others to oppose or support a project. Developers can use the results of this study to anticipate conflict, and determine if mitigation strategies or simply ignoring opposition is the best option. Our results contribute to future work by providing a foundation of knowledge upon which researchers can build. This work will be expanded to include a model that developers will be able to use to predict the financial impacts of potential controversy.

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Blended Analysis of Occupational Safety Hazards and Risk Assessment Approach in the Construction Industry

Changcui Qiu and Xinming Li

1 Introduction

Given the complex existence of the constructional working environment in most construction industries, the study of the construction hazards and their associated risk assessment is limited due to their regulatory-based and reactive nature [8]. Workers were unaware about the risks as they were effective in performing jobs, and each inattention to detail or acceptance on a sub-standard situation of tasks or so called "deviance normalization" moved them into a state of "individual complacency" that can cause more injuries [17]. There have been increasing reports of negative occupational and health effects associated with construction industry. Systematic and statistical analysis on occupational risk and safety hazards is ubiquitous to construction accident research. Meaningful data with correlation can be extracted from number of industry injury reports to generate useful results. The risk evaluation and potential correlation inferred from the recent studies contribute effective risk identifications and help identify potentially risky activities and constructional hazards. Quantitative evaluation and method are often more feasible, and arguably more reliable when considering large number of exposures and accidents. Thus, having the ability to quantitatively examine the occupational performance by utilizing industry injury reports is key from both practical and economical perspectives.

One prominent way to investigate the occupational risk and hazard interrelationship is through the attribute-based approach. This powerful approach allows the baseline characteristics of construction risk attribute to be uniquely defined and any constructional incident cases can be interpreted as the resulting outcome based on the

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occurrence of significant safety risk attributes [13]. The attribute-based risk model for measuring safety risk was first introduced in 2012 [4] and has become widely popular in recent research [13]. The present study focuses on a blended analysis on construction-related injury reports based on the attribute-based risk approach together with degree of risk assessment to determine the level of injury and their corresponding risk controls and preventions. More than 180 construction-related injury reports will be used to investigate, and data mining analysis will also be explored to further analyze the associations and potential linkage of potentially risky activities and constructional hazards with evidence of correlation matrix visualization. Results from this blended analysis deliver overview of the potential risk factors causing unforeseen injuries and illnesses to identify specific tasks that are linked to these risk factors. It could provide further knowledge of how to mitigate the injuries and illnesses.

2 Literature Review

The existing literature on construction industry with attribute-based approach reveals comprehensive guideline and knowledge baseline. The attribute-based risk model for measuring safety risk was first introduced in 2012, the study scrupulously utilized an attribute-based identification with identified 34 fundamental attributes [4]. Through this analysis, they conducted over 300 injury reports from national database and obtained the relative risk values by quantifying safety risks. These risk attribute values can be integrated into the risk assessment to further enhance the techniques of hazard and risk identification. However, the safety risk quantification strategy of this framework was limited by the quantified link between various frequency of exposure and their relation to the magnitude of potential outcome [4]. Consequently, all subsequent result and analysis is based on the unit risk that only focus on the frequency and severity of the incident. To address this limitation, this study utilized degree of risk assessment to further quantify risks associated with frequency of exposure, incident probability and potential consequence.

More recently, the study of leading indicator, precursor analysis and safety risk assessment are also an important and practical source of information for developing prevention strategies and this will help with identification and grouping of keywords. Based on the methods of safety prediction, Hallowell et al. [7] draw on a close study of a unified model on integration of risk assessment. The research team proposed the model that has been organized into four operationally defined families. More specifically, the leading indicators presented in Hallowell's paper help to contextualize the findings on quantity of safety management and activities [7]. Many other studies have attempted to classify application of various key factors by using distinctive visual representation of all significant factors influencing injury analysis [1, 9, 10].

There have been many studies investigating the quantitative soft computing techniques. Ciarapica [3] and his team has also considered the probability and consequences of injuries based on soft computing techniques for identifying general factors. In comparison with commonly used correlation models, the study shows strategies for handling the inter-relationships among different variables. In addition to this concept, Liao and Perng [11] and Tam et al. [14] also concluded important characteristics of occupational hazards examination by using data mining analysis on key factors contributing to construction related injuries in Taiwan. Another existing method based on an automated content analysis is also useful for providing the overall data mining methodology that focus on the relationship between text mining and safety assessment, and specifically how keywords detection can be used for contributing to the fundamental hazardous attributes [16]. Within these broad studies, literature that focused on the blended analysis is expected to help the construction industry, panelized construction or even house manufacturing identify relationships on causes of hazards, key safety attributes, source of injuries and ergonomic characteristics, as well as the level of injury and their corresponding risk controls and preventions.

3 Methodology

To present a blended analysis of the occupational safety hazard and risk assessment, construction-related injury data is examined in this study through three indices, one of which refers to the initial data preparation while the other two refer to the attribute-based risk analysis with degree of risk assessment and the data mining-based analysis. The detailed research process flow that used in this study is summarized in Fig. 1. The process is explained in detail, as follows.

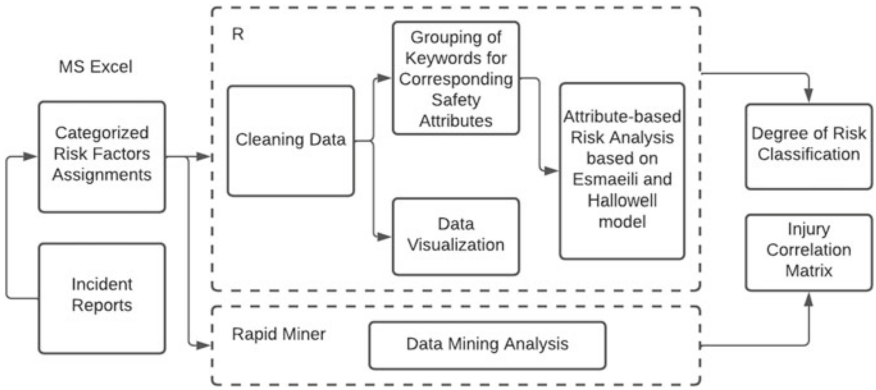

Fig. 1 Detailed research process flow

3.1 Initial Data Preparation and Process Flow

The blended analysis approach developed in this study provides a quantitative evaluation on the occupational risk, which is used to assess the level of injury and the occurrence of serious injury cases. Objectives of this study were fulfilled with the attribute-based risk analysis and the data mining analysis, in perspective with the Occupational Safety and Health (NIOSH) procedures, emphasizing the dominant cause of injuries and its interrelation with the human body. Incident injury cases are first collected from over 180 construction-related injury reports from a collaborative industry partner. In an attempt to identify the related cause-and-effect considerations and keywords, the study then characterized factors based on each performance of the injury reports in the following categories: 6 ergonomic risk factors, 7 safety hazards, 14 area of injuries, 15 equipment and source of injuries and 13 motion injuries summarized in Table 1.

In the pre-processing stage, these factors are assigned to each reported case to ensure an in-depth understanding of the injury outcome. Example of injury reports database are provided in Table 2. The availability, quality and reliability of the data will also be assessed [5]. After completing the initial data management, each corresponding assigned risk factor was prepared for the quantification of the risk based on the attribute-based framework of [4]. The R programming language was mainly used for classification, grouping of keywords and visualization in this section. To further expose the relationships, visualization, and relation analysis of potentially hazardous activities and building hazards, data mining analysis is then carried out following the attribute-based risk assessment model by using the RapidMiner.

Table 1 Pre-assigned categorized factor for cause-and-effect relationship

Motion injuries	Equipment and source of injuries	Area of injuries	Safety hazards	Ergonomic risk factors
Carrying, craning, driving, exiting, falling, kneeling, lifting, nailing, pulling, pushing, slipping, swinging, walking	Crane, falling object, foreign object, hammer, heavy object, ice, ladder, machine, metal item, mud, nail gun, propane, trailer, vehicle, wrench	Ankle, arm, back, chest, face, finger, foot, hand, head, hip, knee, leg, shoulder, wrist	Inadequate maintenance, inadequate clearances, inadequate guards and protection, inadequate PPE	F/P, forceful exertions, poor posture, R/P, repetition, vibration

[*] Noticed that F/P in the following figure can be interpreted as ergonomic risk factors that contain both forceful exertions and poor posture and R/P can be viewed as ergonomic risk factors that represent both repetition work and poor posture

Table 2 Example of injury reports with assigned risk factors

Report	Ergonomic risk factors	Safety hazards	Area of injuries	Equipment and source of injuries	Motion injuries
Was lifting a lift point, from my jig to install on stair cage and felt something tweak/pop just above my tail bone in the middle of my spine	F/P	N/A	Back	Heavy objects	Lifting

3.2 Attribute-Based Risk and Degree of Risk Assessment

The purpose of this task is to determine the magnitude of safety based on the framework of attribute-based risk model together with the degree of risk assessment. To establish the reliability of the safety attribute in accordance with the primary attributes introduced by the Esmaeili and Hallowell [4], in total 11 safety attributes were identified with modifications. This study first employed the R programming language for preprocessing database as mentioned in Fig. 1, specific cleaning process included: upper-case and lower-case conversion as R is case sensitive, omission of N/A variable and extra space elimination.

Next, R will perform the grouping of keywords for corresponding safety attributes for the realization of each attribute. For example, in attribute “Workers moving equipment and object, loading material”, key motion injury words such as “carrying”, ‘pulling” and “pushing” were utilized and contributed for this corresponding attribute. After identifying the proper list of safety attributes, a method employing quantification of risk value was then applied. Instead of considering the quantification method introduced by Baradan and Usmen [2], this study based on the degree of risk equation presented by the Government of Alberta Occupational health and safety Program (OHS) [6], illustrated by Eq. 1.

$$\text{Degree of Risk} = \text{Frequency of Exposure} \times \text{Incident Probability} \times \text{Potential Consequence} \tag{1}$$

Equation 1 uses three factors to analyze the risk: frequency of exposure, incident probability and potential consequences of loss. In Eq. 1, Frequency of Exposure represents the level of exposure to the hazard at the workplace when individual completes a job by considering with each safety attribute. In most cases, this frequency of exposure can be treated as the frequency in which an employee performs the task. Noticed that this factor is more abstract in its nature because activities and hazards can sometimes be seasonal. Therefore, this study will adopt human judgments when considering this factor as the construction-related injury reports can be

Detailed level of classification	Frequency of Exposure	Frequency	Incident Probability	How Often	Potential Consequences	Injury Type
4	Daily	Task is performed one or more times a day	Probable	May happen at least once a month	Severe	Lost Time Claim
3	Weekly	Task is performed once a week	Occasional	May happen once every 1-4 month	Substantial	Medical Aid
2	Monthly	Task is performed once a month	Remote	Not likely to happen, but possible once every 4-12 months	Minor	First Aid Injury or Property Damage
1	Occasionally	Task is performed less than once a month	Improbable	Not likely to happen	Occasionally	Near Miss

Fig. 2 Detailed level of classification for frequency of exposure, incident probability and potential consequences [6]

both complex and dynamic. To limit the scope of the study, this study mainly focused on the frequency of exposure that specially addressed for each task (per job) instead of per entire company.

As shown below in Fig. 2, four different levels (or four score values) of frequency of exposure were pre-defined based on the safety standards adopted from OHS [6] and was used in the ultimate degree of risk calculation. In Eq. 1, Incident Probability in this study indicates how likely is the exposure (or identified safety attribute) will result in loss. The loss in this case can be viewed as any injury, illness, property damage, poor work quality or even lost production. The scale of the incident probability was modified within the appropriate time frame with respect to the given database. To effectively group by each safety attribute within certain level of timeframe, R was used to achieve this goal.

In addition to the scaling modification as mentioned before, the incident probability factor for Fig. 2 also considers the identified safety attribute without current occupational control mechanisms in order to perform a consistency check for each listed attribute. Similarly, Potential Consequence in this study represents how severe will be the loss for each attribute at the workplace if the exposure is not controlled. Potential consequence can be easily quantified by counting number of injury types (Lost Time Claim, Medical Aid, First Aid, Property Damage and Near Miss) that corresponds for each safety attribute. To eliminate inconsistencies among types of injuries identification, if same number of levels of potential consequences has been detected, then the one that contained more severe case was chosen for a consistent purpose.

In accordance with measurements provided by the OHS [6], each degree of risk can be classified into certain range of levels or scores. Low risk refers to the degree of risk from score 1 to 9, this suggests that continued operation is permissible with minimal controls and recommends track the risk and take steps if the risk level increases. Score of 12–27 represents medium risk and it often take timely action to implement appropriate controls to lower or minimize it. Score of 32–64 indicates high risk and it requires immediate action.

After conducting all level of classification for each safety attribute based on Eq. 1, the degree of risk can then be determined by multiplying the values (or scores) of the three factors together according to the previous formula. By analysing the degree of risk scores, safety attributes can then be classified as high, medium, or low risks. This classification will help to establish the priority for the implementation of control measures, and more specifically, to identify relative safety attributes with medium or high risks.

3.3 Data Mining-Based Assessment

Data mining analysis is then conducted following the attribute-based risk assessment model to further reveal the associations, visualization, and correlation coefficient of potentially risky activities and constructional hazards based on pre-assigned categorized factor (see Fig. 1) for each injury cases. The focus of this section of the paper is mainly on text-mining and text-association analysis by using RapidMiner with matrix visualization. With this information, one can more effectively target on specific tasks and relationship based upon the techniques of text-mining and text-association. In this phase, this research utilized different modules and operators to identify and reveal further correlation among associated risk factors. As illustrated in Fig. 1, after assigning categorized risk factor for each reported case, dataset was transformed into the RapidMiner to relate all these attributes together for each case. The schema provides the integrity of the data and eliminates redundancy. In addition, it links all pieces of information together which results in finding high risk industry and occupation conditions to be able to provide administrative and engineering control actions to mitigate their risks. Moreover, it stores data in convenient metadata to be ready for further processing and information extraction. Detailed data processing includes (1) handling text column, (2) preparing data for correlation calculation, (3) encoding-performs one-hot encoding since there is no target on the data and eliminate columns with too much nominal values, (4) removing ineffective columns like constants, (5) sampling data down based on the number of attributes, (6) ordering columns alphabetically and finally (7) creating the actual correlation matrix. The correlation matrix operator in RapidMiner can be used to calculate the correlation between all provided variables. The output weights are normalized, so that the highest score is 1 and the lowest is 0.

4 Results and Discussion

To illustrate the analysis of the occupational safety hazard and risk assessment, the current study developed a blended scheme to conduct both attribute-based risk with degree of risk analysis study and data mining-based analysis on over 180 construction-related injury reports. The main results are stated as following:

4.1 Attribute-Based Risk and Degree of Risk Analysis

Table 3 reveals all relevant degree of risk with detailed quantitative results as well as administrative and engineering control. A list of 11 attributes were identified based on the attribute-based model of Esmaeili and Hallowell and three major groups (Motion and Physical characteristics, Workstation and Jobsite and Equipment, Material and Source) have been classified in regards with all corresponding safety attributes.

An overview of the degree of risk analysis based on the aforementioned attribute model is shown in Fig. 3. This figure is intended to reveal the distribution of each safety attribute with respect to its own determined risk degree, and thus determines the level of risk and the magnitude of safety. By referring to the high-risk zone (light grey shaded area on the top) of the Fig. 3, one can see that “workers moving equipment, and object, loading material”, “working with repeated exposure to high levels of vibration or swinging motion”, “working with heavy equipment” and “working near sharp bladed, metal items or edges” have the highest degree of risk and can be interpreted as the most hazardous attributes for the given construction-related injury cases. These findings are in align with the studies by Thomson [15] where majority equipment related accidents associate with lack of compliance following OSHA regulations and safety standards [15]. By examining at attribute individually, working near sharp bladed, metal items or edges was the most prominently risky attribute. Workers should be taught steps they can take individually to reduce their exposures.

In parallel with this, visualization that implemented by R was also used to reveal the distribution of injury area data with respect to each categorized risk factor as shown in Fig. 1, and thus provide further information of important baseline characteristics of the dataset. Figure 4 as following shows the relationship between area of injuries and four categorized incident risk factors.

As can be seen above, mostly frequently reported ergonomic risk factors were submitted by poor posture and forceful exertions; major equipment source of injuries was resulted in heavy object and nail gun; working from height, inadequate PPE and inadequate clearances contributed to the major safety hazards; nailing, carrying, slipping and lifting motions resulted in most cases. By showing area of injury focused relationship, the visualization has also revealed an overlapping characteristic with the medium or high-risk safety attributes (See Fig. 3) and these findings again are consistent with the previous quantitative results. These risks can be significantly reduced by practicing NIOSH checklist. For example, WMSD Hazard Identification Checklist, Risk Factor Report Card, Workstation Checklist and Task Analysis Checklist [12]. Other suggestions that can possibly reduce the body injuries include establish control measure such as Personal Protective Equipment (PPE): dust masks, proper gloves, hard hats, protective eyewear and steel-toed safety boots [12].

Table 3 Degree of risk classification and controls for each safety attribute

Safety attribute	Frequency of exposure	Incident probability	Potential consequences	Degree of risk classification*	Administrative and engineering control
Motion and physical characteristics					
Working in swing zone of crane	4	2	1	L	Operational policy
Workers moving equipment and object, loading material	4	4	2	H	Avoid manual task and overexertion
Lack of vision or visibility	1	2	2	L	Use of automatic detection
Falling from high work area (scaffold, ladder, and roof)	3	3	3	M	Training, operational policy
Lifting heavy materials	4	3	2	M	Lifting strategy
Working with repeated exposure to high levels of vibration or swinging motion	4	4	2	H	Reducing excessive motions
Workstation and jobsite					
Working in confined space and jobsite with lack construction cleanup	4	3	2	M	Regular construction cleanup
Roadway vehicular accidents	3	4	2	M	Proper Training
Equipment, material and source					
Working with heavy equipment	4	4	2	H	Limits controls
Improperly securing heavy materials/machinery (working under or near lifted loads)-onsite	4	4	1	M	Securement and appropriate protection
Working near sharp blades, metal items, or edges	4	3	3	H	Proper PPE

**L* Low risk, *M* Medium risk, *H* High risk

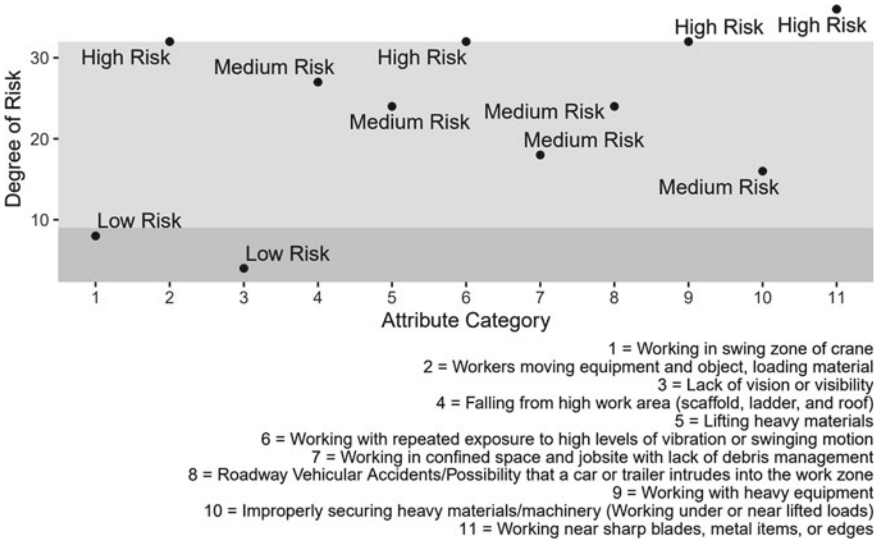

Fig. 3 Detailed degree of risk for each attribute category

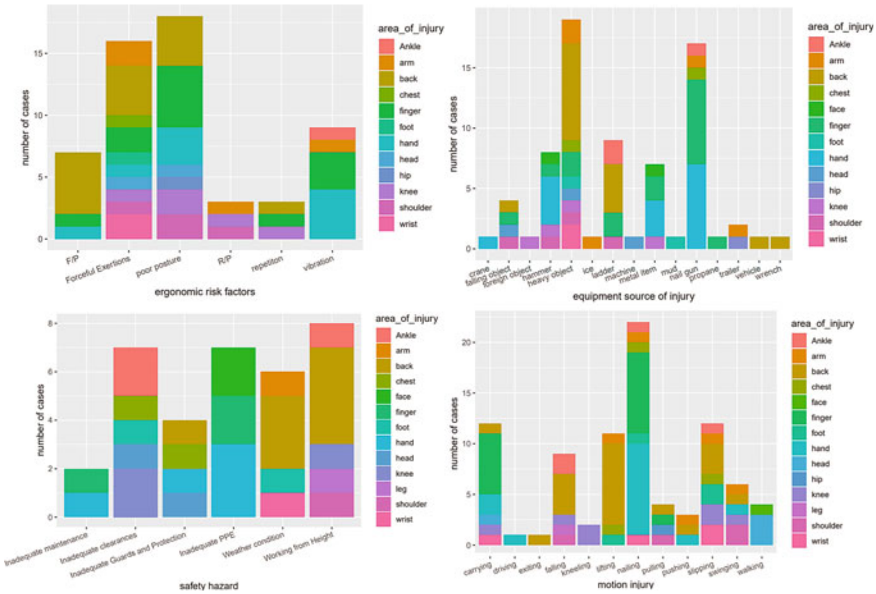

Fig. 4 Number of cases in area of injury by ergonomic risk factors, equipment and source of injury, safety hazards and motion injury

4.2 Data Mining-Based Analysis

In parallel with the attribute-based risk assessment, data mining method was also used to provide the correlation coefficients of important attributes. Table 4 was summarized based on this study's finding with regard to the correlation matrix. As can be seen in Table 4, the correlation measures the degree of association between two attributes and a more positive value for the correlation implies a positive tendency and association. Again, injuries associated with these two highly correlated attributes were observed to be closely relevant to the previous results and discussions. The same results were observed when considering safety attributes for "workers moving equipment, and object, loading material", "working with repeated exposure to high levels of vibration or swinging motion", "working with heavy equipment" and "working near sharp bladed, metal items or edges". Attributes that relate to nail gun, vibration and nailing are coupled and this again show consistency of the data mining results. Moreover, other than commonly correlated attributes, industries and administrators should also acknowledge the following associated correlation: wrist injury with trusses, wrist/hand injury with wall, back/arm injury with wrench and back/hand injury corresponds with working at heights. The findings indicate that one can utilize

Table 4 Matrix visualization—relative injury correlation matrix with coefficient

First correlated attribute*	Second correlated attribute	Correlation coefficient
Equipment/source of injury = heavy object	Motion injury = lifting	0.749
Motion injury = falling	Safety hazard = working from height	0.730
Area of injury = wrist	Equipment source of injury = trusses	0.704
Area of injury = wrist/hand	Equipment source of injury = wall	0.704
Equipment source of injury = nail gun	Ergonomic risk factors = vibration	0.653
Equipment source of injury = falling object	Safety hazard = inadequate guards	0.580
Area of injury = back/arm	Equipment source of injury = wrench	0.572
Area of injury = back/hand	Safety hazard = working from height	0.572
Ergonomic risk factors = vibration	Motion injury = nailing	0.558
Ergonomic risk factors = F/P*	Motion injury = lifting	0.532

*One should note that the negative or inverse association for the correlation are not shown in the table. F/P can be interpreted as ergonomic risk factors that contain both forceful exertion work and poor posture these correlated results to effectively achieve safety measurements and preventive actions to minimize the likelihood of potential hazardous occurrence.

5 Conclusions

Complexity on construction hazards control and occupational risk management has been a major concern in modern construction industry. Quantification method based prospective studies and analysis of the risk factors and characteristics on injury incident reports makes valuable contributions. This paper presents a blended study on occupational risk assessment, in perspective with both attribute-based and data mining approaches. By applying the distinctive quantitative analysis on level of injuries and knowledge of constructional hazard into over 180 incident reports in a case study, this paper explores a strategy of degree of risk classification, attribute-based identification, and data mining correlation. By referring to the results, one can see that attributes such as "workers moving equipment, and object, loading material", "working with repeated exposure to high levels of vibration or swinging motion", "working with heavy equipment" and "working near sharp bladed, metal items or edges" have the highest degree of risk which can be interpreted as the high risky characteristics in cases of construction-related injuries. Correlation coefficients performed by data mining further justified the importance of these attributes. The blended research is intended to help the construction industry recognize associations between hazard factors and ergonomic elements, as well as the extent of injuries and the risk controls and preventions corresponding to them.

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Resource Sharing: Singularity Function Cooperative Game

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Notation

A	Resource area
C	Cost of machine
c	Unit cost of machine ($/d)
DUR	Activity duration
f	Finish
M	Resource moment
MC	Marginal contribution
N	Total numbers of players
r	Resource
S	Sub coalition
s	Start
$u(y)$	Unit cost function
v	Payoff

1 Introduction

Subcontractors play essential roles in a successful project because they often perform most of the scope of work. Although general contractors coordinate with subcontractors to perform construction tasks, there are still many conflicts that can occur on

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site due to limited spatial size, shortage of equipment, lack of materials, etc. These issues lead to inefficient resource management and eventually cause a project to be over budget and schedule. The complexity of construction projects might lead firms to focus on addressing their own needs first. Collaboration is always best for the project and can be beneficial for its participants. For these reasons, subcontractors are always encouraged to cooperate effectively to not only solve the current issues, but also increase the respective profits for the individual [8].

Efficiently managing resources is one of the keys to having successful projects. General contractors seek to recruit 'good' subcontractors to perform tasks and share risks [1]. During execution, the contractor usually coordinates with subcontractors to get the project completed while minimizing risk. In situations of lacking resources, the contractor needs to coordinate subcontractors to obtain or relocate said resources. The contractor has tools at their disposal to facilitate a smooth project progress, including resource leveling and resource allocation techniques. In past decades, researchers have therefore studied finding effective methods that can support resource sharing. Perera [7] developed a resource-hour unit model that uses linear programming to maximize the rate of construction and the resource requirements in linear projects. Leu and Hwang [4] presented a shared resources model using a genetic algorithm technique that produced optimal or near-optimal solutions. Liu et al. [5] studied construction equipment to aid clients in settling resource-leveling issues compared with conventional methods. Xu et al. [11] expressed the principle of resource sharing in space and time and developed a dynamic programming-based genetic algorithm to prove the efficiency of the model in the optimization. Nevertheless, the aforementioned methods are not necessarily best suited to handling insufficient resources in complex projects, nor do they explicitly address potential cooperation.

1.1 Knowledge Gap

In the construction industry, parties face challenges when working in teams or partnering, which here will be referred to as forming a *coalition*. One of such challenges is resource sharing (i.e., tower cranes, batch plants, etc.) that can be found in many construction projects in practice. Resource sharing can benefit the project with respect to being completed on time and within budget. In other words, resource sharing can reduce risk. But resource sharing is normally neither well controlled by general contractors nor subcontractors. Issues that may hamper or preclude it are questions such as priority of using a shared resource, how to distribute the resource reasonably, or how to weigh the percentage of its workload versus the benefits that the resource provides. Such factors can cause conflicts, inefficient resource use, or, in the worst case, disagreements and disputes among subcontractors. Moreover, as construction projects become more complex with many parties, resource sharing needs not just an experienced contractor, but a formal model to fairly share the resources and redistribute the savings that are realized as profits by such sharing.

A research need therefore exists for an optimal model that efficiently solves the resource sharing problem for a group of subcontractors, as well as prove that the feasible solutions will lead to a stable coalition in terms of profitability for each party. This paper posits that *game theory* can provide such a needed model.

2 Methodology

2.1 Goals and Objectives

The new model is developed with two goals in mind; (1) utilizing resources appropriately to maximize profits while remaining a clear and simple method to be used under field conditions; and (2) ensuring the fairness of allocating profits among subcontractors within a coalition. The desired optimization will merge relevant concepts of cooperative game theory as well as singularity function and address four objectives:

- Developing a resource-sharing model with multiple scenarios;
- Integrating cooperative game theory with singularity functions;
- Quantifying fairness of allocating shared resources and profits;
- Validating the model with an illustrative application example.

2.2 Model Development

The basis of the model is an integration of cooperative game theory and singularity function that not only maximizes resource capacity and profits, but also fairly allocates the profits among related participants.

2.2.1 Singularity Functions

Singularity functions are continuous functions that can accommodate discontinuities—the eponymous singularities. They were first applied in civil engineering, specifically in structural analysis of beams and plates under loads to efficiently determine shear and moment. Equation 1 presents the fundamental definition of one term of a singularity function per Wittrick [10], which is indicated by a pair of pointed brackets.

$$s \cdot \langle x - a \rangle^n = \begin{cases} 0 & for\ x < a \\ s \cdot \langle x - a \rangle^n & for\ x \geq a \end{cases} \tag{1}$$

where x = variable under consideration; a = lower boundary of the current segment, i.e. the singularity where a phenomenon starts to exist; exponent n = order of said phenomenon; and s = scaling coefficient.

2.2.2 Resource Histogram

A resource profile (also called histogram) can be plotted to visualize the number of resources that exist over a certain period of time. Such histograms can be expressed with singularity functions by stating the resource rate r, start time s, finish time f, and duration of an activity. As Lucko [6] explained, a model with k activities (or resources) has $2 \cdot \mathrm{k}$ terms due to writing a positive and negative r_i, as per Eq. 2. Both r and s are variables. Note that r being variable means that the finish is the start plus the duration, where duration is the resource content (i.e. area A in the histogram in worker-days) divided by the resource rate.

$$r(y) = \sum_{i=1}^{2\cdot k} \left(r_i \cdot \langle y_{i\_\max} - s_i \rangle^0 - r_i \cdot \left\langle y_{i\_\max} - s_i - \frac{A_i}{r_i} \right\rangle^0 \right) \tag{2}$$

2.2.3 Cooperative Game Theory

Cooperative game theory describes games of multiple players who agree to cooperate toward a mutual goal [2]. Cooperative game theory can thus be directly applied to resource sharing to assist subcontractors fairly split costs and profits under resource constraints. The proposed framework seeks stable coalitions, for which costs and profits can then be split once the project has been completed.

2.2.4 Shapley Value

Shapley [9] introduced a powerful metric to fairly allocate the shared assets (payoffs, outputs) among players based on their known marginal contributions (inputs) into coalitions. Per Eq. 3 the Shapley value averages the marginal contributions of players who are involved in a grand coalition (i.e. with all players).

$$\phi_i = \frac{1}{N!} \cdot \sum_{i=1, i \in S, S \subset N}^{N} [(|S| - 1)! \cdot (N - |S|)! \cdot MC(i)] \tag{3}$$

where S = subcoalition; N = grand coalition; and MC = marginal contribution. The marginal contribution of player i to coalition S is the added value to a coalition when that player enters into that group per Eq. 4.

$$MC(i) = MC(S) - MC(S - \{i\}) \tag{4}$$

2.2.5 The Core

In game theory, the Core serves as a tool for measuring the stability of a coalition. The Core is a set of feasible shares of the coalition's worth across the players [3]. The Core is called empty when players are incapable to form coalitions or only an unstable coalition exists. A stable coalition of players must satisfy the following three properties of efficiency, individual rationality, and coalitional rationality:

Efficiency: $\sum_{i \in N} x_i = v(N)$. Benefits (payoffs) x_i that members i of a coalition get in a cooperative game are listed in a vector $x = (x_1, x_2, \ldots, x_n)$ and is efficient if their sum equals the worth of the grand coalition $v(N)$.

Individual rationality: $x_i \geq v(\{i\}), \quad \forall i \in N$. Members act economically rational and want to get at least as much payoff in a coalition as they would receive if they acted individually, i.e. not within any coalition.

Coalitional rationality: $\sum_{i \in S} x_i \geq v(S), \quad \forall S \subset N$. The sum of payoffs in a subcoalition must be at least the subcoalition worth. This is a stable core (i.e. a set of solutions exists). Else the core unstable (empty).

2.2.6 Cost Function

The cost function C indicates how much a subcontractor spends on the resources in their activity and is also expressed as a singularity function. Cost is the unit cost multiplied by the activity duration per Eq. 5.

$$C(Act_i) = u_i \cdot \langle y - s_i \rangle^1 - u_i \cdot \left\langle y - s_i - \frac{A_i}{r_i} \right\rangle^1 \tag{5}$$

$$f_i = s_i + \frac{A_i}{r_i} \tag{6}$$

where $u =$ unit cost function; other variables in Eqs. 5–6 are the same as for the resource histogram. The unit cost function u models how the unit cost changes depending on activity duration per Eqs. 7 and 8.

$$u(y) = \sum_{j=1}^{end} \left[c_j \cdot \langle y - s_{sj} \rangle^0 - c_j \cdot \langle y - sf_j \rangle^0 \right] \tag{7}$$

$$u(y) = c_1 \cdot \left[\langle y - s_{s1} \rangle^0 - \langle y - s_{f1} \rangle^0 \right] + \ldots + c_n \cdot \left[\langle y - s_{sn} \rangle^0 - \langle y - s_{fn} \rangle^0 \right] \tag{8}$$

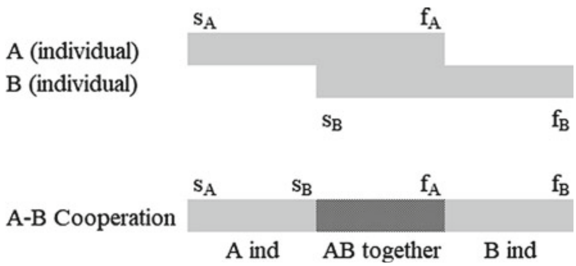


Fig. 1 Individual and joint work

where c = unit cost per time period; s_s = start time; s_f = finish time; and j = unit cost index.

Individual work is defined as a subcontractor who prefers to work on an activity alone. Such subcontractor will be solely responsible for their duration, cost, and profit. On the other hand, *joint work* is defined as subcontractors who allow placing their resources into a pool for sharing. Once tasks are completed, cost and profit must be fairly split among them. Hence the total cost of activities is also determined in terms of individual and joint work. In some of scenarios of resource sharing, joint work may be more beneficial than individual work, because only then may a large resource be utilized to its capacity. Equation 9 indicates the total individual cost (C_S) as the sum of the subcontractors' individual activity costs. Meanwhile Eq. 10 is the total joint cost (C_N) as the difference of total individual costs and total joint cost (i.e. activities and their resources overlap). The overlapped part, as shown in Fig. 1, is the *cost savings* C_Δ of the grand coalition, where N = total subcontractors within a coalition; A = resource area; r = resource rate; s = start time; f = finish time; u = unit cost function; k = index indicating the earliest activity ($s_k \leq s_i$); j = subcontractor index where ($j \neq$ k); [j] = combination of several subcontractors participating in a coalition.

$$C_S = \sum_{i=1}^{N} C(Act_i) = \sum_{i=1}^{N} \left[u_i \cdot \langle y - s_i \rangle^1 - u_i \cdot \left\langle y - s_i - \frac{A_i}{r_i} \right\rangle^1 \right] \tag{9}$$

$$\begin{aligned} C_N &= \sum_{i=1}^{N} [C(Act_i) - C_\Delta] \\ &= u \cdot \left[\langle y - s_k \rangle^1 - \langle y - f_k \rangle^1 \right] \\ &\quad + u \cdot \left[\langle y - \max(s_{j+1}, f_j) \rangle^1 - \langle y - \max(f_{j+1}) \rangle^1 \right] + \cdots \end{aligned} \tag{10}$$

3 Illustrative Example

A hypothetical example of three subcontractors X, Y, and Z is analyzed to determine the optimal resource sharing in their construction project. These subcontractors initially choose to rent three machines to erect a building. But it is assumed that only one machine can be used on site because of spatial limitations. To ensure that the work will progress smoothly, the subcontractors decide to use only one machine. The ongoing capacity needs of the subcontractors from the machine are X (40%), Y (50%), and Z (60%).

3.1 Inputs

Table 1 shows the unit cost of the machine. Table 2 lists inputs including start, finish, activity duration, resource rate, possible shifts, and capacity use of the machine. From the capacity use, possible coalitions of the subcontractors can be formed as XY = 90%; XZ = 100%; YZ = 110%; and XYZ = 150%. As a result, XZ and XYZ are over the maximum capacity of the machine (100%). These coalitions are breaking the rules of the game for three-players and thus creating an infeasible solution. One must now reschedule by reducing the resources rates and/or shifting the activities along the time axis to reach a feasible solution. Figure 2 shows the information of graphically to visualize the resource versus duration trade-off.

Table 1 Machine unit cost

Range	Rental period	Unit cost ($/day)
c_1	0–5 days	15
c_2	6–7 days	13
c_3	8–10 days	10

Table 2 Illustrative example data

Time	Before			After		
Subcontractor	X	Y	Z	X	Y	Z
Start [d]	0	2	3	0	1	0.67
Duration [d]	4	6	7	8	8.57	9.33
Finish [d]	4	8	10	8	9.57	10
Resource Rate [–]	2	1	2	1	0.7	1.5
Capacity [%]	40%	50%	60%	20%	35%	45%
Possible Shifts [d]	(0, 6]	[−2, 0); (0, 2]	[−3, 0)	(0, 2]	[−2, 0); (0, 0.57]	[−0.67, 0)

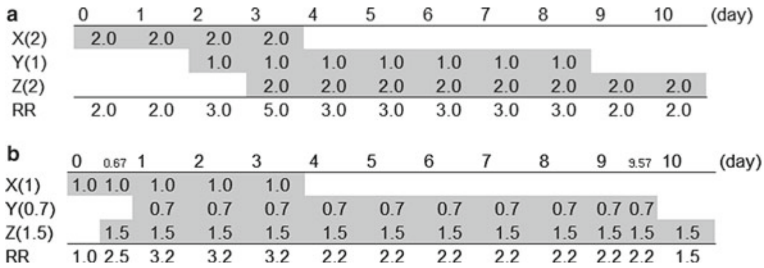


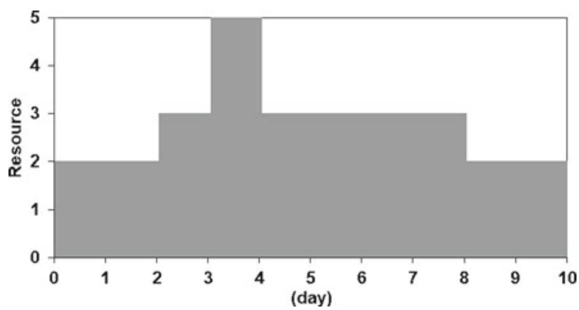
Fig. 2 **a** Schedule before resource sharing. **b** Schedule after resource sharing

3.2 Resource Histogram

The initial resource profile is composed of additive singularity functions as per Eq. 2 to give Eqs. 11–13. Equations 11–13 and Fig. 3 represent the resource histogram before forming coalitions and potentially reducing activity productivities while extending durations to fit within the machine capacity. Note the ratio of *A* and *r* in each second term. Subcontractors X, Y, and Z perform their activities with required crane uses of 40%, 50%, and 60%, respectively, which sums to 150%, accordingly, the activity productivities must be reduced. Here it is assumed that r_x drops from 2 to 1, r_y from 1 to 0.7; and r_Z from 2 to 1.5 to obey the 100% limit and in proportion to this, their capacity uses drop from 40 to 20%; 50% to 35%; and 60% to 45%, respectively. These values can be negotiated and splitting savings of resource sharing fairly will be analyzed in the following step. Equation 14–16 give the adjusted resource profiles after reducing the productivities and extending durations proportionately, i.e. having different finish terms. Further results could be found by shifting activities to the left or right. Figure 4 shows one of several solutions. The optimization of the resource sharing is needed, but it is currently out of the scope of this paper.

$$r(y)_X = 2 \cdot \langle y - 0 \rangle^0 - 2 \cdot \left\langle y - 0 - \frac{8}{2} \right\rangle^0 \tag{11}$$

Fig. 3 Resource profile before resource sharing



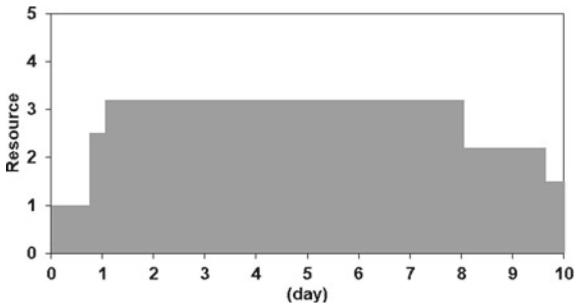


Fig. 4 Resource profile after resource sharing

$$r(y)_Y = 1 \cdot \langle y - 2 \rangle^0 - 1 \cdot \left\langle y - 1 - \frac{6}{1} \right\rangle^0 \tag{12}$$

$$r(y)_Z = 2 \cdot \langle y - 3 \rangle^0 - 2 \cdot \left\langle y - 3 - \frac{7}{2} \right\rangle^0 \tag{13}$$

$$r(y)_X = 1 \cdot \langle y - 0 \rangle^0 - 1 \cdot \left\langle y - 0 - \frac{8}{1} \right\rangle^0 \tag{14}$$

$$r(y)_Y = 0.7 \cdot \langle y - 1 \rangle^0 - 0.7 \cdot \left\langle y - 1 - \frac{6}{0.7} \right\rangle^0 \tag{15}$$

$$r(y)_Z = 1.5 \cdot \langle y - 0.67 \rangle^0 - 1.5 \cdot \left\langle y - 0.67 - \frac{7}{1.5} \right\rangle^0 \tag{16}$$

3.3 Feasible Coalition

The Core analyzes the feasibility and stability of coalitions. Subcontractors only form coalitions if they satisfy *efficiency, individual,* and *coalitional rationality* as shown in the following system of inequalities.

Efficiency: $x_X + x_Y + x_Z = v_{XYZ}$.

Individual rationality: $\begin{cases} x_X \geq v_X \\ x_Y \geq v_Y \\ x_Z \geq v_Z \end{cases}$

Coalitional rationality: $\begin{cases} x_X + x_Y \geq v_{XY} \\ x_X + x_Z \geq v_{XZ} \\ x_Y + x_Z \geq v_{YZ} \end{cases}$

To validate the Core for the grand coalition, consider two scenarios, which will be called *formable* and *unformable coalition.* In the *unformable coalition*, capacity uses of X, Y, and Z are 40%, 50%, and 60%. Thus, only two subcontractors can cooperate

Table 3 Assumed profits

Coalition	Unstable	Stable
X	$0	$0
Y	$0	$0
Z	$0	$0
XY	$80	$54
XZ	$70	$44
YZ	$80	$54
XYZ	$90	$90

below the machine capacity (XY and XZ). Accordingly, the grand coalition forms an empty Core while the Core exists for smaller coalition of two players. But another scenario is a formable coalition. Here the capacity uses of X, Y, and Z are 20%, 35%, and 45% capacity. Three subcontractors are eligible to form a coalition because the overall machine use is below 100%. But it has not yet been determined if the Core is stable or unstable. To identify the Core, the game will be analyzed in regard to *unstable* and *stable coalitions*. For this, it is additionally assumed that no extra profit is earned by working alone; but there is some extra profit in subcoalitions per Table 3. The profits in Table 3 are illustrative to represent the stability of the Core in developing coalitions.

For an unstable coalition, the inequality system does not satisfy the aforementioned core conditions:

$$\begin{cases} x_X \geq 0, \quad x_Y \geq 0, \quad x_Z \geq 0 \\ x_X + x_Y \geq 80, \quad x_X + x_Z \geq 70, \quad x_Y + x_Z \geq 80 \\ x_X + x_Y + x_Z = 90 \end{cases}$$

where $2 \cdot (x_X + x_Y + x_Z) \geq (80 + 70 + 80) \Rightarrow (x_X + x_Y + x_Z) \geq 135$. Since the total profits of X, Y, and Z is $90, there is no set of profits satisfies this condition. Thus, the Core is unstable. For a stable coalition, the inequality system needs to satisfy the Core conditions:

$$\begin{cases} x_X \geq 0, \quad x_Y \geq 0, \quad x_Z \geq 0 \\ x_X + x_Y \geq 54, \quad x_X + x_Z \geq 44, \quad x_Y + x_Z \geq 54 \\ x_X + x_Y + x_Z = 90 \end{cases}$$

where $2 \cdot (x_X + x_Y + x_Z) \geq (44 + 54 + 44) \Rightarrow (x_X + x_Y + x_Z) \geq 71$. The total profits of X, Y, and Z ($90) is greater than the condition ($71). This has a set of the profit satisfying the above condition, stabilizing the Core that allows for resource sharing and increasing the contractors' benefits. Hence, there are sets of X, Y, and Z will be ranged from $71 to $90. At this point, the Core can be used to determine a stable coalition of subcontractors sharing the resource. Calculating the cost is needed to fairly redistribute their savings.

3.4 Cost Functions

Equation 17 models the entirety of Table 1 for the *unit cost u* that a subcontractor pays for renting the machine.

$$\begin{aligned} u(y) &= 15 \cdot \left[\langle y-0\rangle^0 - \langle y-5\rangle^0\right] + 13 \cdot \left[\langle y-5\rangle^0 - \langle y-7\rangle^0\right] \\ &\quad + 10 \cdot \left[\langle y-7\rangle^0 - \langle y-10\rangle^0\right] \\ &= 15 \cdot \langle y-0\rangle^0 - 2 \cdot \langle y-5\rangle^0 - 3 \cdot \langle y-7\rangle^0 \end{aligned} \tag{17}$$

In case the subcontractors do not collaborate, the cost of the machine would be paid by each subcontractor individually. Meanwhile, subcontractors who share the machine for any period of time split its cost then and individually will pay less than the individual renting. Equations 18–20 are subcontractors X, Y and Z who perform their tasks alone. And Eqs. 21–24 are coalitions XY, XZ, YZ, and XYZ. Equations 25–28 determine relative cost savings when subcontractors form a coalition as indicated in the index.

$$C_X = u_X \cdot \left[\langle y - 0\rangle^1 - \langle y - 8\rangle^1\right]_X \tag{18}$$

$$C_Y = u_Y \cdot \left[\langle y - 1\rangle^1 - \langle y - 9.57\rangle^1\right]_Y \tag{19}$$

$$C_Z = u_Z \cdot \left[\langle y - 0.67\rangle^1 - \langle y - 10\rangle^1\right]_Z \tag{20}$$

$$C_{XY} = u_{XY} \cdot \left[\langle y - 0\rangle^1 - \langle y - 9.57\rangle^1\right]_{XY} \tag{21}$$

$$C_{XZ} = u_{XZ} \cdot \left[\langle y - 0\rangle^1 - \langle y - 10\rangle^1\right]_{XZ} \tag{22}$$

$$C_{YZ} = u_{YZ} \cdot \left[\langle y - 0.67\rangle^1 - \langle y - 10\rangle^1\right]_{YZ} \tag{23}$$

$$C_{XYZ} = u_{XYZ} \cdot \left[\langle y - 0\rangle^1 - \langle y - 10\rangle^1\right]_{XYZ} \tag{24}$$

$$\begin{aligned} C_{\Delta XY} &= u_X \cdot \left[\langle y - 0\rangle^1 - \langle y - 8\rangle^1\right]_X + u_Y \cdot \left[\langle y - 1\rangle^1 - \langle y - 9.57\rangle^1\right]_Y \\ &\quad - u_{XY} \cdot \left[\langle y - 0\rangle^1 - \langle y - 9.57\rangle^1\right]_{XY} \end{aligned} \tag{25}$$

Table 4 Cost and profits

Cost	X	Y	Z	$\sum C_{Act}$	C_N	C_Δ
X	$80	$-	$-	$80	$80	$-
Y	$-	$86	$-	$86	$86	$-
Z	$-	$-	$93	$93	$93	$-
XY	$80	$86	$-	$166	$96	$70
XZ	$80	$-	$93	$173	$100	$73
YZ	$-	$86	$93	$179	$93	$86
XYZ	$80	$86	$93	$259	$100	$159

$$C_{\Delta XZ} = u_X \cdot \left[\langle y - 0\rangle^1 - \langle y - 8\rangle^1\right]_X + u_Z \cdot \left[\langle y - 0.67\rangle^1 - \langle y - 10\rangle^1\right]_Z - u_{XZ} \cdot \left[\langle y - 0\rangle^1 - \langle y - 10\rangle^1\right]_{XZ} \quad (26)$$

$$C_{\Delta YZ} = u_Y \cdot \left[\langle y - 1\rangle^1 - \langle y - 9.57\rangle^1\right]_Y + u_Z \cdot \left[\langle y - 0.67\rangle^1 - \langle y - 10\rangle^1\right]_Z - u_{YZ} \cdot \left[\langle y - 0.67\rangle^1 - \langle y - 10\rangle^1\right]_{YZ} \quad (27)$$

$$C_{\Delta XYZ} = u_X \cdot \left[\langle y - 0\rangle^1 - \langle y - 8\rangle^1\right]_X + u_Y \cdot \left[\langle y - 1\rangle^1 - \langle y - 9.57\rangle^1\right]_Y - u_Z \cdot \left[\langle y - 0.67\rangle^1 - \langle y - 10\rangle^1\right]_Z - u_{XYZ} \cdot \left[\langle y - 0\rangle^1 - \langle y - 10\rangle^1\right]_{XYZ} \quad (28)$$

Table 4 summarizes costs and profits for all coalitions as calculated by the previous singularity functions. This information now finally allows determining the fair benefit allocation to each member of a coalition.

3.5 *Cost and Profit Allocation (Marginal Contribution)*

To calculate the correct marginal contribution, one can include the weight of the contribution by using the Shapley value. The marginal contribution of the subcontractors was calculated in term of cost in Eq. (25–28). For example, for subcontractor X, the corresponding Shapley value is $\phi_X = (1/3 \times \$0 + 1/6 \times \$70 + 1/6 \times \$73.3 + 1/3 \times \$73.3) = \$48.3$ per Eq. 29. The integration of Shapley value within the singularity functions enables for simultaneously sharing the resource while defining the fair share for each subcontractor. Similar to ϕ_x, Shapley values for Y and Z are calculated and summarized in Table 5.

$$\phi_X = \frac{1}{3} \cdot 0 + \frac{1}{6} \cdot \left(u_X \cdot \left[\langle y - 0\rangle^1 - \langle y - 8\rangle^1\right] + u_Y \cdot \left[\langle y - 1\rangle^1 - \langle y - 9.57\rangle^1\right] - u_{XY} \cdot \left[\langle y - 0\rangle^1 - \langle y - 9.57\rangle^1\right]\right) + \frac{1}{6} \cdot \left(u_X \cdot \left[\langle y - 0\rangle^1 - \langle y - 8\rangle^1\right] + u_Z \cdot \left[\langle y - 0.67\rangle^1 - \langle y - 10\rangle^1\right]\right.$$

Table 5 Contribution and profit allocation

Subcoalition	Saving	Weighted			Players			Marginal		
-	C_D	X	Y	Z	X	Y	Z	X	Y	Z
X	$0	0.333	–	–	$0	$0	$0	$0	$0	$0
Y	$0	–	0.333	–	$0	$0	$0	$0	$0	$0
Z	$0	–	–	0.333	$0	$0	$0	$0	$0	$0
XY	$70	0.167	0.167	–	$70	$70	$-	$11.7	$11.7	$0
XZ	$73	0.167	–	0.167	$73	$-	$73	$12.2	$0	$12.2
YZ	$86	–	0.167	0.167	$0	$86	$86	$0	$14.3	$14.3
XYZ	$159	0.333	0.333	0.333	$73	$86	$89	$24.4	$28.6	$29.7
Shapley value								$48.3	$54.5	$56.2

$$-u_{XZ}\cdot\left[\langle y-0\rangle^1-\langle y-10\rangle^1\right]\Big)$$
$$+\frac{1}{6}\cdot\Big(u_X\cdot\left[\langle y-0\rangle^1-\langle y-8\rangle^1\right]-u_{XYZ}\cdot\left[\langle y-0\rangle^1-\langle y-10\rangle^1\right]$$
$$-u_{YZ}\cdot\left[\langle y-0.67\rangle^1-\langle y-10\rangle^1\right]\Big) \tag{29}$$

3.6 *Stability of Solution*

The overall solution {$48.3, $54.5, $56.2} are the profits of subcontractors X, Y, and Z, respectively. This solution is checked to satisfy the following inequality system. All conditions are satisfied, so the Shapley value {$48.3, $54.5, $56.2} is an appropriate solution for the coalition with *a non-empty* and *stable* Core.

$$\begin{cases} x_X\geq 0,\quad x_Y\geq 0,\quad x_Z\geq 0\\ x_X+x_Y\geq 70,\quad x_X+x_Z\geq 73,\quad x_Y+x_Z\geq 86\\ x_X+x_Y+x_Z=159\end{cases}$$

4 Conclusions and Future Work

4.1 *Contributions to the Body of Knowledge*

Lacking tools to efficiently and fairly share resources in a grand coalition has been a challenge that may prohibit or hamper potentially beneficial collaboration between subcontractors on construction projects. The research has established a flexible model using singularity functions to share resources, find stable coalitions among subcontractors, and fairly divide the savings. The presented paper contributed to the body of knowledge by (1) expressing the resource profiles via singularity functions, that allows schedulers to modify activity productivity or shift the histogram while automatically updating the activities' start and finish dates; (2) providing insights that can motivate subcontractors to cooperate, as they can maximize profit and reduce risk by sharing underutilized resources with others, which is both economic and sustainable; and (3) determining feasible and stable solutions that satisfy the interests of all members in a coalition, while ensuring that such internal optimization does not impact the planned project completion.

4.2 Recommendations for Future Research

Future work could explore the realm of possible optimal solutions and prioritize them by additional parameters, so that general and subcontractors will gain ranked options for suitable schedules that avoid conflicts, ensure fairness, maximize profits, and foster a collaborative environment. The proposed framework needs to account for uncertainties that can impact the overall resource utilization. This will provide the decision makers with a comprehensive understanding on the resource sharing potential. Finally, the framework needs careful testing on multiple case studies to further validate the model that will support the construction industry by providing the means for further collaboration.

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Cost Production and Utilization in Collaborative Delivery Methods in the Construction Industry

P. Martel, D. Forgues, and C. Boton

1 Introduction

Construction projects are widely varied, often unique and complex, and require large teams trained specifically for each project. While the major phases of project delivery are universal (see Fig. 1), the methods used to implement them and to train project teams vary across delivery methods.

1.1 Traditional Method of Production

The construction industry is an important part of the economy and has been the subject of much research since the late twentieth century. The reports describe the many problems it suffers from, including a lack of predictability of costs [6]. And the traditional way of doing business is no stranger to these problems.

The traditional delivery method uses a sequential process, where a new phase does not start until the previous one is completed. It also uses a project team, usually formed on a competitive basis, where the lowest bidders are selected. The selection and arrival of each part of the team depends on the phase of the project, so that the team, small at the beginning, becomes progressively larger as the phases are completed, and is finally complete during construction (see Fig. 2).

This delivery method has a long history and is widely adopted in the construction industry, to the point where it has become "safe" to use it, despite the fact that it does not always produce the best value for the client [5]. The difficulties it generates can

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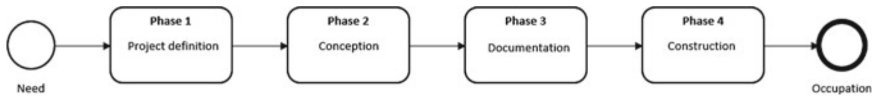

Fig. 1 The main phases of a project's implementation

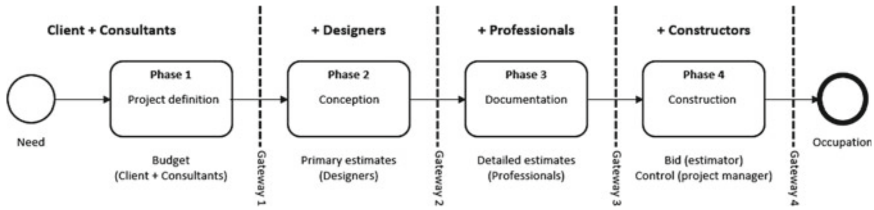

Fig. 2 Traditional process

be grouped under two aspects. The first concerns the relational dynamics within the team itself, arising mainly from the contractual method. The second is the difficulties and shortcomings arising from the project definition process.

1.2 The Collaborative Approach

To address these difficulties, Fewings [4] proposes an integrated approach to project management, where the client is actively involved in the project team, while eliminating the separations between design and construction. He also proposes the integration of several processes, including risk management, value engineering, time planning, cost control, quality control and functional analysis. This approach has resulted in initiatives worldwide, including *Integrated Project Delivery* (IPD) in the United States of America [2] and the *Alliance Contract* in Australia [3]. They have in common that they aim to optimize the project in a positive relational context within the project team, and, notably, the results report excellent predictability in costs.

2 The Research Project

2.1 Background

The *École de technologie supérieure de Montréal* (ÉTS) has been conducting various research projects for several years on techniques and processes applicable to the construction industry, specifically aimed at improving the overall performance of the industry. In 2019, an opportunity arose to study two companies that have in common the use of some form of project team integration for the construction of their buildings. The first company has all the components of a project team in-house: developer, operators, professionals, general contractor, and various specialty contractors. The second company uses the IPD collaborative project delivery method. Both companies retain ownership of the buildings constructed, which they operate with their team. This research focuses on the production and cost utilization processes of the projects undertaken by these firms.

2.2 Methodology

This study is based on action research, a method that is well suited to research in applied disciplines such as construction [1]. The data was drawn from case studies at the two partner companies, supplemented by a literature review focusing on the generation and use of costs in construction, and the management of construction projects. The case studies and the literature review were conducted in parallel in a mutually enriching cycle.

For the first case study (Case Study 1), data were obtained from three separate sources: immersion observation, semi-structured interviews and documentation provided by the company. The immersion took place over a two-week period, the first in the team's corporate offices and the second on the construction team's premises. The observer also attended two (2) project team meetings, the first one for a project located at the "documentation" phase and the second one for a project located at the "construction" phase, a meeting of the BIM team for the deployment of the 5D, a coordination meeting of the construction team and a last meeting for the closing of a tender for an external project to the company. Following the immersion, fifteen (15) semi-structured interviews were conducted with employees occupying significant positions in the production and use of costs throughout the entire project process. Finally, the company provided the research team with twenty-two (22) organizational charts, twenty (20) process maps and role and responsibility matrices, digital mock-ups of two (2) current projects and three (3) estimation structures.

For the second case study (Case Study 2), the data was drawn from the same sources as for the first case study. The immersion consisted of participating as an observer in three work sessions with the project team. Eleven (11) semi-structured interviews were conducted, first with the owner's team, then with the contractor's team and professionals; the "snowball" technique was used to expand the list of interviews. Finally, the company made available to the research team the contract binding the parties of the project team.

3 Case Study 1—Vertically Integrated Company

Founded some 60 years ago, the company had approximately 350 employees at the time of the study. As a large landowner, it develops, builds, and operates its own properties. These properties include industrial, commercial, and residential buildings. A major restructuring took place in 2018, following a spin-off of the company. Inspired by new entrepreneurial trends in construction, it undertook a major review of its structure and processes. It was in the context of the implementation of BIM 5D in the company that the study was conducted.

3.1 Project Team

3.1.1 Company Structure

Two of the company's four (4) executive vice-presidencies are directly involved in the projects. The "Asset Planning and Development" executive vice-presidency includes the project office, site planning, architecture, and asset management; it is responsible for identifying and planning projects to be carried out. The "Operations" executive vice-presidency brings together all the teams involved in construction, property management, and engineering; it is responsible for carrying out projects. Under the executive vice-presidencies, the company is structured into entities that are like those generally found in the industry: urban planning, architectural and engineering offices, general and specialized contractors, and operators. These entities are relatively autonomous and behave in much the same way as those in industry. Physically, the company's workforce is housed in two separate buildings: administration and professionals in an office building and contractors in an industrial building.

3.1.2 Project Implementation

The data collected show that the administrative structure is reflected in the execution of projects. For example, separate processes were adopted by each of the executive vice-presidencies: one process for the first two phases of a project and one for the two subsequent phases. Although the documentation provided by the company suggests that there is an intention to involve some of the second team in the definition and design of the projects, the observations show that these processes are more like silos (Fig. 3).

The data from the immersion and semi-structured interviews are consistent overall. However, some of them are not congruent with the data from the analysis of the documentation provided by the company, particularly those concerning compliance with certain milestones set out in the formal processes.

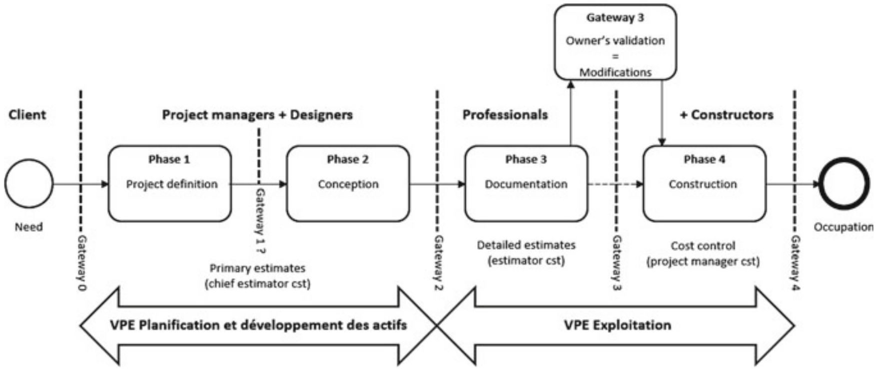

Fig. 3 Summary process company 1

Several interviews highlighted that the processes related to phases 1 and 2 were not really respected and that the lack of precision in the project objectives implied several reworkings. One person mentioned that "the boss's vision is in his head and it's not easy to know it," and later added, "one of my challenges is to improve the definition of the project and get a real green light before going to design or preparing plans and specifications … this would eliminate all these time-consuming requests for revisions and changes." Interviews also revealed that there is no life-cycle value analysis of the building, with the acquisition cost being the only decision criterion. Another interviewee mentioned that it is possible to introduce innovation into projects: "We built a thermal plant for one development, and we are currently doing a pilot project in another development to test a new way of armouring the slabs."

All the data agree that phases 3 and 4 are like those observed in the traditional project implementation process. Two discrepancies were reported by the interviewees. The first concerns the estimates carried out by one of the general contractor's estimators with the support professionals to answer the questions. The other discrepancy is the lack of a formal submission, which one of the interviewees regretted: "I would like to see a real submission once the plans are 100% complete … that would make it possible to analyze (product) options and avoid having to make changes when leaving for the site."

The interviews also confirmed that the handover of the building to the operations team is done in the same way as in traditional projects: "… I get ring binders with the documentation … (but) we don't have time to read that and as we don't have a maintenance management system yet, there is no motivation to do it." Finally, the operations team is not involved in either the project definition or the design: "We don't have enough hindsight to pass on operating data."

3.1.3 Relationships

The immersion allowed us to observe the dynamics of relations within the company, both at the team level and at the employee level. The general atmosphere is cordial, and the employees have a positive view of the company. The people interviewed identify areas for improvement and want to participate in them. However, some difficulties are apparent.

First, the obligation of financial results for each team leads to reflexes like those observed in the industry; thus, as observed during one of the meetings, there is a distribution of "extras" between the "client," the "professional" and the "contractor." One interviewee also noted, "when it's outside of our normal delivery, we ask for an increase in our project budget … we stick to our annual budgets."

The immersion also found that the physical separation between two locations tends to entrench a separation between the "contractor" and the rest of the employees. Employees in one building know each other well, but generally do not know those in the other building.

3.2 Production and Use of Costs

The production and use of costs in the firm is very similar to that in the general industry. The main distinction is that the production of estimates is done by the general contractor's estimating team, while the professionals focus on project design and documentation.

3.2.1 Production of Costs

In phases 1 and 2, summary estimates are prepared by the contractor's estimating team leader. The interviews indicated that the data used for quantities were calculated at a high level from "mass" sketches and digital mock-ups prepared by the designers and that the unit prices were taken from previous projects. However, as one interviewee pointed out, "for residential projects, we don't have much hindsight and the prices used are not good." Another person also mentioned: "It's (the chief estimator) who makes the estimates, because the estimators are used to making bids based on plans and we don't have that at these phases." During one of the meetings, we noted that the tool used was an EXCEL-type spreadsheet.

In phase 3, an estimator from the general contractor's team is assigned to the project and estimators from trade contractors contribute to the estimate. The interviews, as well as the processes analyzed, confirm that there is an estimate prepared at 40, 80 and 100% completion. However, one of the interviewees emphasized that "there is a lot of information missing to do my job at 40% and even at 80% … I have to make assumptions to cover the whole job." The immersion provided an opportunity to observe the work of the various estimators; they use several different estimating tools that are not or little compatible with each other.

In phase 4, the costs are essentially those from suppliers, subcontractors (the company's "specialty" units are managed as subcontractors), and the company's own labour. The construction project manager has to take the estimated costs and rework them to enable him to do his monitoring: "I take the estimate file and I put together an EXCEL file that I adjust for each project … I make a different breakdown because I have to break the job down according to the phases and contracts I give." For cost control, issuing purchase orders and paying invoices, the company uses another application that is specialized for managing construction contracts.

3.2.2 Use of Costs

The costs produced in phases 1 and 2 are used to prepare the project charter: "my team prepares the project charter … the overall plans, massing studies and preliminary estimates are in the project charter." One interviewee noted, "in principle it allows the Chair to give the project the green light, but since we are usually asked to continue in the interim, changes come as the plans and specifications are advanced and sometimes even as construction begins … there are many reworkings."

In phase 3, the estimates are used to verify that the project meets the estimates established at the end of phase 2. However, the estimating formats are different and make it almost impossible to analyze discrepancies as noted by an interviewee: "the estimates in the project charter are summary and high level, whereas the estimator's estimates are from their software which gives a very detailed breakdown and the totals do not correspond to the same elements as those in the charter… I have to fall back on the total cost, and I cannot point out where the discrepancies are."

In phase 4, the costs are used for the same purposes as in the standard contracts: internal cost control, submission of change requests, payment of invoices and accountability.

3.2.3 Predictability of Costs

The observations show that cost overruns exist for residential projects, for which the company has little experience. The interviewees mentioned that significant savings could be generated if the construction team were involved in the pre-construction phases: "I could submit more varied alternatives to the professionals' choices and we could then save money … when I do it at the beginning of the construction, it is often too late to do it, as the modifications have impacts everywhere."

4 Case Study 2—Company Using IPD Mode for Project Delivery

This Quebec-based company has been operating spas since 2005. In full expansion, it plans to add a dozen sites to its offer, across Canada and the United States. As part of this expansion, the company has turned to a collaborative approach for the realization of its projects, the *Integrated Project Delivery* (IPD). As Quebec first IPD project, ÉTS was asked to document the implementation process for the expansion project of the Quebec site.

4.1 Project Team

4.1.1 Organization

The Quebec facility expansion project was in the definition phase at the time the dipping observations were made. The entire project team was present at the three working sessions attended by the observer. The three main components of the team were as follows:

- Owner: project manager, representative of the company's design team (architect), chief facility operator; internal collaborators were invited as needed.
- Professionals: architects (local firm + external firm with experience in IPD), engineers of all disciplines (national firm).
- Builders: general contractor with IPD experience + major specialty contractors (civil, mechanical, electrical).

The team is separated into sub-teams, also called "pit groups". Each sub-team is responsible for developing and evaluating ideas for the aspect of the project under its responsibility. Typically, the project team meets for a full day of work every two weeks and this day is punctuated by plenary sessions and sub-team work sessions. In between these days, each participant has "homework" to gather the data needed to evaluate the ideas, including likely costs. We observed that the project team uses several techniques to organize its work: brainstorming sessions, pull-planning, agile management, cloud-based digital tools, value analysis workshops and risk identification and mitigation processes.

4.1.2 Relationships Within the Project Team

The contract binding different organizations in the project team is of the IPD type. The contract confirms that the parties share the profits generated during the project and that their own costs will be paid by the project, regardless of the outcome. The contract also provides for audits of the various organizations by the owner to ensure that the costs charged to the project are the actual costs. In his interview, the owner's project manager explained that the choice of partners was made through a process consistent with the company's values: through meeting, presentation and working sessions, the owner and contractor chose each other "mutually." Subsequently, the process was extended to the other partners, with the owner and the entrepreneur acting jointly. One of the objectives mentioned during the interview was to ensure a good "chemistry" in the team.

The immersion allowed us to observe the behaviour of the partners during the working sessions. The atmosphere was generally friendly and respectful. There was no apparent hierarchy in the project team. Participation in activities was intense and creativity (brainstorming) was rampant. Everyone was able to contribute ideas to be explored, even if they were outside their field of expertise. The commitment of the participants in the research and analysis to be completed was easy to find. The owner was present through his team, whose active participation ensured that the company's values and objectives were not lost in the project.

The semi-structured interviews also revealed a consensus among the interviewees. The guarantee of being paid for their costs invested in the project, combined with the sharing of profits and the promise of not being sued, generates a collaboration that goes beyond the usual: "if my team is available and more capable of doing a task, even outside my specialty, then I don't hesitate to do it since it is profitable for everyone… I have sometimes made casting plans that integrated all the specialties to make the contractor's work easier."

4.2 Process of Production and Use of Costs

Observations and interviews confirm that a great deal of effort is expended by the project team in the project definition phase. The main objective is to obtain a very precise definition of the project that considers the real needs of the owner and the issues specific to the project. To optimize the project, the team uses alternative analysis and value engineering workshops. The team also implements a process for identifying and managing risks and opportunities. As one participant pointed out, the effort invested in this phase is quickly recouped during the rest of the project, since there is normally no rework. In the subsequent phases, the project team focuses on improving the shared benefit within the final project parameters. (see Fig. 4).

4.2.1 Production of Costs

At the project definition phase, each sub-team estimates the costs associated with the options they are considering. In an interview, a contractor's representative explained: "once approved during the project definition phase, each pit group becomes responsible for its own estimates throughout the project … this is what keeps the costs

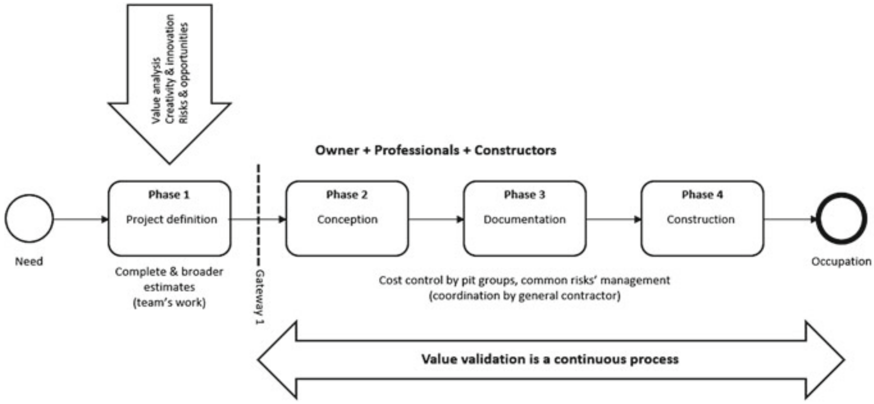

Fig. 4 Summary process enterprise 2

in line." The overall assembly of costs is entrusted to the general contractor's estimator who ensures consistency and follow-up. The interviewees all confirmed that value engineering and risk management are systematically built into the project delivery process: "It goes on until the end of the project … unused allocations increase the pooled profit … you can't cut the cost of materials, but we can find more labour-efficient ways of doing things, like doing a lot more prefabrication."

The data for the estimates vary according to the phases. At the project definition phase, quantities are summarily estimated, sometimes based on sketches, but mostly based on the experience of the participants. Unit costs come from the data banks of each company, from exploratory calls to suppliers, and from evaluations based on experience. Uncertainties and risks inherent in the options studied are assessed and incorporated into the costs in the form of an allowance. In the subsequent phases, more traditional estimates can be made (design, plans and specifications) with the difference that the presence of contractors allows for greater precision. During the work, suppliers and subcontractors are also solicited. The collaboration between professionals and contractors allows them to consider the conditions of the construction site at the beginning of the project.

4.2.2 Use of Costs

Two main uses of costs emerged from the interviews. The first is at the project definition phase, and it boils down to defining the overall cost of the project and the specific costs of each sub-team. As each company is collectively responsible for these costs, it makes a commitment to the owner to respect this overall cost. Subsequently, the costs are essentially used to control the final cost of the project, to identify improvements during the project and to determine the profit of the project.

There are also two interesting features to note. First, the unused portions of the risk envelopes are contributed to the overall project profit; sub-teams are therefore very effective in managing risk. Second, the owner can use his share of the profits to improve the value of the project by authorizing the realization of options identified at the project definition phase.

4.2.3 Predictability of Costs

Interview data from individuals who have previously been involved in projects in this method indicate that not only are the costs estimated at the project definition phase being met, but that the projects typically cost less to complete than traditional projects.

5 Data Analysis

When we look at the predictability of costs, the two case studies show markedly different results. In fact, the results obtained in the first case study are very similar to those obtained in the traditional project delivery method, while those in the second case study tend to demonstrate that the method chosen is clearly more efficient. By comparing the results obtained in the case studies, key elements of the success of the collaborative method emerge.

First, the active and transparent involvement of the owner throughout the process, especially in the project definition phase, seems essential as pointed out by Fewings and Henjewele [5]. In the first case study, the owner of the company is not very involved, only giving general lines to the project direction, which causes many changes later, the efforts required to address these changes are then important and come at a time when the margins of manoeuvres are reduced. In the second case study, the active involvement of the owner ensures that the project is precisely defined and meets clearly identified needs, so that there are very few subsequent changes.

Another key element is the involvement of the entire project team at the project definition phase. Remarkably, one of the shortcomings identified in the first case study interviews was that the absence of the construction team at this phase did not allow for the consideration of possible construction options and as a result, projects were not well optimized, requiring too many changes during construction. In the second case study, the construction team influences the definition of the project by providing expertise and participating in the identification of options, thus ensuring that the project is optimized for construction. In addition, by involving the entire team, including the operators, all costs can be considered, allowing for comprehensive estimates.

The significant effort put into the project definition phase, as observed in the second case study, is another key element of the success of the collaborative method. As mentioned by those who have already participated in collaborative projects, the significant increase in effort at this phase translates into greater efficiency in carrying out the subsequent phases, as the team knows exactly what the project is and does not have to make major changes to the work done. However, for the project definition work to be effective, the team must use methods based on creativity, effective division into multidisciplinary sub-teams, agile work management, mutual respect, and commitment of the participants. This is a significant change from the traditional, highly hierarchical method, like the structure adopted by the company in the first case study.

Also, one of the keys to the success of the collaborative method observed in the second case study lies in the continuous efforts to optimize the value of the project. Thus, sub-teams look for alternatives to products and construction methods that are likely to increase productivity on the site, particularly by calling on innovation. This gap was also highlighted by some of the interviewees in the first case study.

An important element in the overall costs of a project is related to risk management. In this respect, the two case studies show similarities, namely that unused allocations are released to the project. This is an important difference compared to the traditional method where allocations are hidden in the submitted prices and retained by everyone when the project goes well. There is, however, an important difference that was observed between the case studies. In the former, there was no formal process related to the analysis and management of risks and opportunities, whereas in the latter, such a process is formally put in place; thus, the associated costs are well identified so that management becomes effective and the prospect of turning them into profit becomes an excellent motivation to find optimal solutions to problems.

Finally, it should be noted that the motivations of the team members have an important influence on the overall project results. Like the participants in the traditional project method, the project team members in the first case study were particularly concerned with the financial profitability of the administrative unit to which they belong. This has the effect of stifling the collaborative potential of the integrated team, with little incentive for members to invest beyond what is normally agreed to their traditional role. In the second case study, individual motivation towards the project is very high, as everyone is assured of "not losing" in the process. Moreover, the prospect of increasing the collective benefit, shared among the team members, is a powerful driver for individual involvement, creativity, innovation, and optimization of the value of the project. This essential element for the success of the collaborative method observed in the second case study has an influence not only on the costs, but also on the schedule and the quality of the works.

6 Conclusion

This research confirms that the use of a collaborative delivery method can indeed improve project delivery, particularly with respect to cost predictability. However, two important limitations should be noted. On one hand, only two case studies were carried out, and they concerned different approaches. On the other hand, the process studied, the generation and use of costs, is part of a much larger process. It would therefore be appropriate to continue this study in other cases, broadening the scope to the global process, to validate the other contributions of these methods.

Despite their advantages, collaborative methods are not necessarily adapted to all projects, such as simple and standardized works; it would therefore be interesting to push research towards the definition of selection criteria of the methods of realization according to the projects and the objectives of the client. The method of selection and training of teams could also be the subject of further study, especially for public contracts which are highly regulated; a pilot project in this market would make it possible to identify the relevant rules to ensure the fairness of the process.

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Analyzing the Causes of Conflicts and Disputes in Modular Construction Projects

M. Abdul Nabi and I. H. El-adaway

1 Introduction

The construction industry is a significant contributor to the national economy [1]. Although it has a positive economical impact, the construction industry experiences poor overall performance as well as many cost and schedule overruns [2]. To mitigate such poor performance in the industry, previous research studies have suggested different strategies. Some strategies included the need to adopt more innovative methods such as modular construction to increase project performance [3]. On the other hand, some other studies suggested the need to implement robust contract administration practices that minimize conflicts, claims, and disputes in the construction projects and thus improving project performance [4, 5]. To this end, research efforts have been providing guidelines to improve contract administration practices on one hand and focusing on the implementation of modular construction on the other.

Modular construction has been perceived to promote project performance through schedule reductions, cost savings, improved quality, and productivity [6]. Despite the benefits associated with it, modular construction still faces many industry-related challenges and risks that limit the capitalization on its full potentials [7]. For instance, O'Connor et al. [8] highlighted that higher levels of modularization can be achieved if the contractual and technical requirements favor the adoption of such a method. Moreover, Nadim and Goulding [9] emphasized on the need for new processes and contractual models for the implementation of offsite construction methods. To this end, one of the risks associated with the integration of offsite construction methods are related to contractual problems and disputes [10].

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Based on the aforementioned, the use of modular construction methods does not negate the need for proper contract administration practices that minimize conflicts, claims, and disputes in the project; consequently, improving its performance. To achieve that, there is a need to understand the main causal factors of disputes and conflicts in modular construction projects.

2 Goals and Objectives

The goal of this paper to identify the causes of disputes in modular construction projects. To this end, the authors' objectives are to: (1) contemplate disputes and conflicts for actual case studies related to modular construction projects in the United States; (2) highlighting the key causes leading to disputes and conflicts among project stakeholders; and (3) aggregately study the dispute causation mechanisms and leading indicators of disputes in modular construction projects.

3 Background Information

According to Haas et al. [11], Modular construction is defined as "the preconstruction of a complete system away from the job site that is then transported to the site. The modules are large in size and possibly may need to be broken down into several smaller pieces for transport". In fact, the modular construction has been gaining attention during the last decades [12]. Nevertheless, modular construction market is expected to further increase in the short and long term [13]. According to the Global Modular Construction Market Research Report [14], North America has the second largest modular construction market—following the Asia Pacific region—with a market share of 27.6%. Furthermore, the global construction market is forecasted to boom by the end of 2024 with a 9.2% compound annual rate [15]. As such, modular construction market is attracting the attention of the industry. Despite that, there are still obstacles and challenges that are slowing the increase in the adoption rate of modular construction in the market. Some of these challenges include the need for high initial capital cost [6], lack of clear codes and standards [8], increased design and engineering lead-in time [16], and the fragmented nature of contractual agreements [17]. In this paper, the authors focus on the challenges related to contractual agreements by identifying the main aspects of disputes in modular construction projects.

4 Research Methodology

All the detailed methodological steps are provided in this section.

ID	Causes of Disputes	ID	Causes of Disputes
C1	Variations initiated by the owner	C15	Quality of design
C2	Change of scope	C16	Availability of information
C3	Late giving of possession	C17	Ambiguities in contract documents
C4	Acceleration	C18	Different interpretations of the contract provisions
C5	Unrealistic expectations by the owner	C19	Risk allocation
C6	Payment delays	C20	Other contractual problems
C7	Delays in work progress	C21	Adversarial / controversial culture
C8	Time extensions	C22	Lack of communication
C9	Financial failure of the contractor	C23	Lack of team spirit
C10	Technical inadequacy of the contractor	C24	Site conditions
C11	Tendering	C25	Unforeseen changes
C12	Quality of works	C26	Weather
C13	Design errors	C27	Legal and economic factors
C14	Inadequate / Incomplete specifications	C28	Fragmented structure of the sector

Fig. 1 Common causes of disputes (Adapted from Cakmak and Cakmak [18]

4.1 Common Causes of Disputes

To analyze disputes and conflicts in modular construction projects, a list of common causes of disputes is needed. According to Cakmak and Cakmak [18], 28 common causes of disputes in the construction industry were considered based on an extended literature review. The literature review conducted by the authors included previous research papers that were addressing disputes as related to the construction industry in general, or to construction markets with specific geographical areas. The 28 common causes of disputes identified by Cakmak and Cakmak [18] are shown in Fig. 1.

4.2 Collection and Review of Case Studies

The authors collected publicly available case studies related to disputes using Google Scholar. The case studies were selected and collected as to reflect disputes among key stakeholders of projects following the modular approach. Based on that, the authors collected 15 publicly available case studies. The reviewed project disputes were mainly related to residential and nonresidential building sector such as hotels, condominium units, and multifamily housing projects. Furthermore, the case studies included disputes between parties contracted under design-build, construction management, design-bid-build, and purchase type of agreements. Afterwards, the authors thoroughly reviewed each case study and analyzed the main causes that led to the disputes among project stakeholders. The review of case studies was accompanied with the construction of a reference matrix. The reference matrix shall enable the authors document the frequency of occurrence of causal factors in the case studies. The reference matrix is constructed such that the causes are presented as rows and the reviewed case studies as columns. If any of the factors—presented in Fig. 1—is perceived to had caused the dispute and conflict among the stakeholders in the analyzed case study, its corresponding cell value would be equal to 1; otherwise, a value of zero would be entered for the cell.

4.3 Social Network Analysis

SNA was developed originally for social related studies to examine trust, communication, and other social aspects [19]. However, SNA has been recently implemented on different topics related to engineering, construction, and project management [20]. In particular, SNA has been implemented to understand the causation factors of different construction related events. For instance, Aljassmi et al. [21] analyzed the root causes of defects and ranked them using SNA centrality measures. Furthermore, Eteifa and El-adaway [22] modeled the root causes of fatalities in construction using SNA. Following the same logic, the authors will use SNA to analyze the causes of disputes and conflicts in modular construction projects. The detailed adopted steps in analyzing the causes of disputes are present in the upcoming subsections.

4.3.1 Construction of Adjacency Matrix

To conduct SNA on the analyzed case studies, an adjacency matrix shall be constructed directly from the data gathered in the analysis of case studies (i.e. reference matrix). Such conversion provides a symmetric matrix where the rows and columns reflect the causes of disputes, and the cell values represent the co-occurrence frequency of each cause in the analysis of case studies. The adjacency matrix is derived—as shown in Eq. 1—by multiplying the reference matrix by its transpose and then substituting the diagonal entries of the matrix product by zeros.

$$A_{n\times n} = \begin{cases} R_{n\times m} \times R^{T}_{n\times m} & for\ i \neq j \\ 0 & for\ i = j \end{cases} \tag{1}$$

where $A_{n\times n}$ is the adjacency matrix and n equal to the total number of disputes causes (i.e. 28); $R_{n\times m}$ is the reference matrix and m equal to the number of analyzed case studies (i.e. 15); and $R^{T}_{n\times m}$ is the transpose of the reference matrix with i and j being the indices of the reference matrix rows and columns, respectively.

4.3.2 SNA Measures

After constructing the adjacency matrix, the authors used SocNetV 2.5 software package to plot the network diagram and compute the centrality metrics for each causal factor. In this study, the authors focus only on the co-occurrence of the causes in the analyzed case studies. Thus, an undirected network is assumed to present

Table 1 Adopted SNA metrics

SNA measure	Description	Context
Network density	The proportion of the potential connections that are actualized among the nodes of the network [22]	Extent of interconnectivity among the dispute causes in the network
Weighted degree centrality	The sum of all edges' weights connected to a given node [22]	Total number of times a cause has co-occurred with other causes in the analyzed disputes and conflicts
Eigenvector centrality	The eigenvector of the adjacency matrix largest eigenvalue [22]	This metric reflects to what extent a given cause co-occurs with other central causes. In other words, importance is quantified in terms of number the cause connections and their quality

the nodes (causes) and connections of the adjacency matrix. Furthermore, the main step towards the analysis of the dispute causation using SNA is to select relevant measures and understand their context to dispute causation network. To this end, the authors adopted four SNA measures for the analysis of the dispute causation network including weighted network density, degree centrality, and eigenvector centrality. Table 1 shows the SNA measures used in this paper along with their description and context to the scope of this paper.

The network density is computed by find the fraction of the total number of actual connections (edges) in the network with respect to the total number of eligible connections in the network as shown in Eq. 2.

$$Network\ Density = \frac{Total\ number\ of\ actual\ connections}{\frac{n \times (n-1)}{2}} \quad (2)$$

where $\frac{n \times (n-1)}{2}$ is the total number of possible connections in the dispute causation network with n equal to the number of nodes (causes of disputes) in the network, which is 28.

Furthermore, and to compute the weighted degree centrality of each cause of dispute, the authors used Eq. 3.

$$DC_i = \sum_{j:j \neq i} y_{i,j} \quad (3)$$

where DC_i is the weighted degree centrality of causal factor i; and $y_{i,j}$ is the value in the ith row and jth in the adjacency matrix.

Finally, the eigenvector centrality is computed by solving Eq. 4.

$$\lambda x = Ax \tag{4}$$

where A is the adjacency matrix; λ is the eigenvalue of adjacency matrix A; and x is the eigenvector of adjacency A and eigenvalue λ. It is worth noting that x is nothing but the eigenvector centralities of the causal factors.

5 Results and Analysis

This section presents and analyzes the obtained results.

5.1 Dispute Causation Network

Based on the reference matrix derived from the analysis of case studies, the authors constructed the adjacency matrix using Eq. 1. The cell values of the adjacency matrix represent the weight of the edge from one node to another. Figure 2 shows the cell values of the adjacency matrix in a color-coded format. The cells are color-coded according to the strength or weight of the edges between each pair of causes. As shown in the figure, the pair of causes having white colored cells indicate that they have not co-occurred in any of the analyzed disputes. An example for the latter would be C3 (Late giving of possession) and C27 (Legal and economic factor). On the other hand, some pair of causes possess dark green cells indicating high weights and thus abundant co-occurrence in the analyzed disputes and conflicts. The latter is reflected in the weights of edges between C22 (Lack of communication) and C23 (Lack of team spirit).

Afterwards, the authors utilized the adjacency matrix to plot the dispute causation network as shown in Fig. 3. The network diagram is comprised of 28 causes (nodes) connected by 274 undirected edges or links. It can be noted from the figure that the network includes many connections between the dispute causes. In fact, the dispute causation network seems dense indicating many inter-connectivities among the causal factors. The edges weights or strengths are not presented in the figure due to the high edge density and consequently poor network readability.

The authors computed an SNA metric called network density to quantify the inter-connectivities among the dispute causes. The computed network density was found equal to 0.721 indicating relevantly high interconnectivities among the causes of disputes. This reflects that disputes are the result of multiple co-occurring causes rather than of a single causal factor. However, one can note that C5 (unrealistic expectations by the owner) does not have any ties or connections with the other dispute causes. The latter reflects that none of the analyzed disputes seems to be caused from unrealistic expectations of the owner. The following subsections discuss the centrality measures obtained for each causal factor in the network.

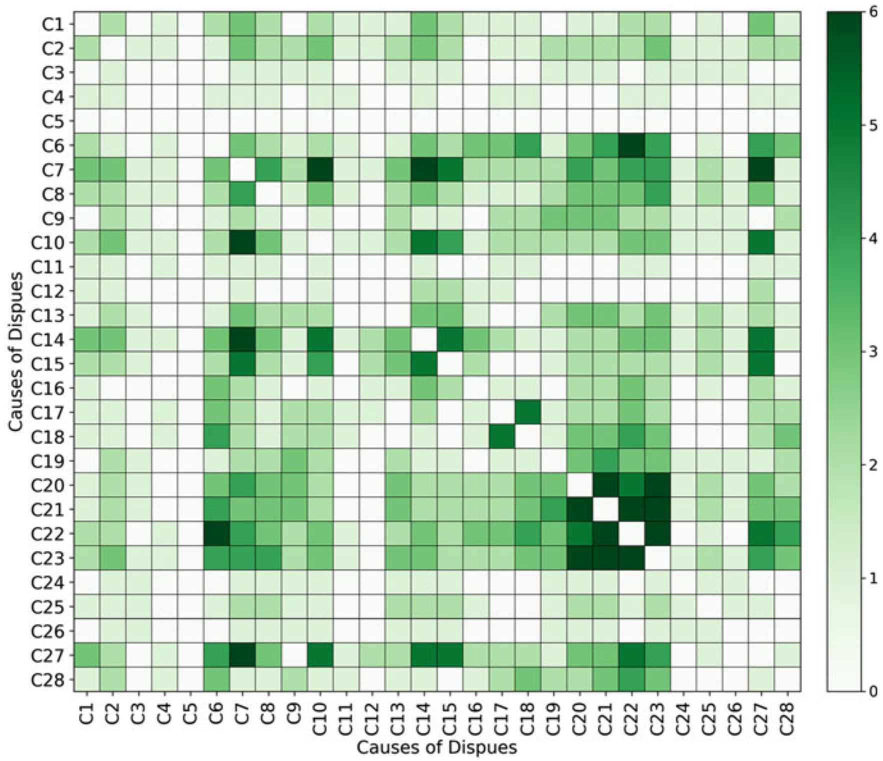
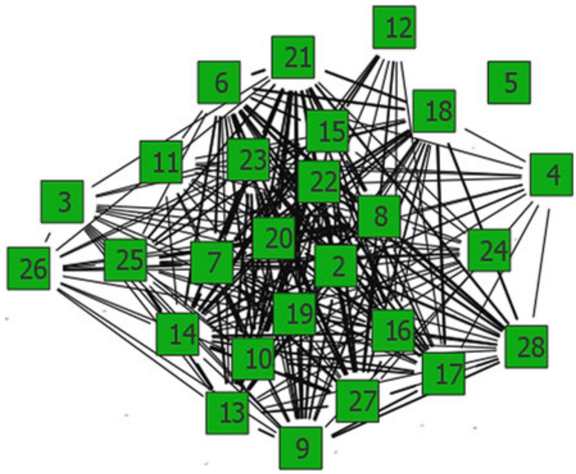


Fig. 2 Adjacency matrix

Fig. 3 Dispute causation network



5.2 SNA Centrality Measures

As discussed in the methodology, the authors utilized two main centrality measures including the weighted degree centrality and eigenvector centrality. The centralities associated with each cause of dispute are shown in Table 2.

According to the obtained weighted degree centralities, C7 (delays in work progress), C23 (lack of team spirit), and C22 (lack of communication) are the top three central causes of disputes in modular construction projects. The latter indicates that C7, C23, and C22 are the most co-occurring causes of disputes in the network.

Table 2 SNA results

Causes	Weighted degree centrality	Eigenvector centrality
C1	34	0.145
C2	44	0.174
C3	15	0.057
C4	14	0.058
C5	0	0.000
C6	55	0.237
C7	73	0.297
C8	50	0.208
C9	34	0.136
C10	58	0.239
C11	14	0.058
C12	12	0.051
C13	41	0.173
C14	64	0.255
C15	49	0.205
C16	30	0.137
C17	37	0.154
C18	41	0.175
C19	38	0.160
C20	62	0.262
C21	65	0.272
C22	71	0.301
C23	72	0.296
C24	15	0.057
C25	28	0.116
C26	15	0.057
C27	63	0.271
C28	36	0.152

Furthermore, the eigenvector centralities consider these causes among the top three central causes of disputes. As such, it can be concluded that C27, C23, and C22 are not only important due to their frequent co-occurrence with other causes in the network but also due to their interconnectivities with other central and important causes. In other words, these three causal factors are associated with other critical causes that may lead collectively to disputes and conflicts in modular construction projects. Furthermore, and by comparing the results of both centrality measures, the causes are similar with only minor differences in their rankings. To this end, it is evident that delays in work progress, lack of team spirit, and lack of communication are among the main factors leading to disputes in modular construction projects.

6 Discussion of the Research Findings

For this section, a detailed discussion will be conducted on the top three factors that were identified to be central causes of disputes in modular construction projects.

6.1 Delay in Work Progress

The results show that delays in work progress (C7) is considered a central cause of disputes in modular construction projects (ranked # 1 by degree centrality and # 2 by eigenvector centrality). In fact, modular construction methods are perceived to reduce disruptions and delays due to less congested workplace, reduced interfaces among the various activities and trades, as well as reduced impact of severe weather conditions [23]. However, there are also different challenges that may lead to delays in modular construction projects such as inadequate logistics, planning, among others [24, 25]. A relevant example would be one of the analyzed case studies where the dispute between the contractor and owner arose due to delays in the project. Some of the main reasons of delays were related to site accessibility issues, the unfamiliarity of workers with modular construction, and lack of coordination between offsite and onsite activities.

6.2 Lack of Team Spirit

The results show that lack of team spirit (C23) is considered a central cause of disputes in modular construction projects (ranked # 2 by degree centrality and # 3 by eigenvector centrality). In fact, a successful implementation of modular construction requires an increased level of collaboration among project stakeholders [26]. Modular approach requires the involvement of and collaboration between the owner, architect, and contractor starting from the early phases of the project [27]. This aligns with O'Connor et al. [28] who stated that a critical success factor to modular construction projects is to avoid disconnects in any contractual transition between assessment, selection, Basic Design, or Detailed Design phases. For instance, in one of the analyzed case studies, the contractor has not been involved in the design process of the project leading to many conflicts and changes to the design and thus delay in the project. In fact, the contractor in this case study clearly highlighted that the lack of adequate collaboration with the entire design team further impacted the project through increased delays.

6.3 Lack of Communication

The results show that lack of communication (C22) is considered a central cause of disputes in modular construction projects (ranked # 3 by degree centrality and # 1 by eigenvector centrality). In fact, lack of proper communication among project stakeholders and challenges in coordination are considered as main barriers to modular construction projects [29]. The latter explains why advances in information technology such as Building Information Modeling is perceived to further promote the use of modular construction in the industry [30]. Such communication shall increase the level of collaboration among the stakeholders and improve coordination as related to submittals, site management, deliveries of modules, thus, reducing delays in work progress. For example, along with the increased project delays and the lack of collaboration with the design team, the contractor in of the analyzed case studies have suffered from delayed responses to decisions or submittals. This was highlighted by the contractor who noted that the turn around time frame for the approval and review process of submittals and requests for information was considered high leading to accumulation of delays in the project.

7 Conclusion and Future Work

The authors followed a multi-step methodology to identify the causes of disputes in modular construction projects. First, the authors collected and analyzed 15 actual national case studies reflecting disputes in modular construction projects. Second, social network analysis was conducted where frequency analysis and various SNA metrics were used to identify the top causes of disputes as well as understand the dispute causation network in modular construction projects. The analysis of the dispute causation network shows that disputes and conflicts require the co-occurrence of more than a single causal factor. The latter is reflected by the high interconnectivities among the causes of disputes in the network. Furthermore, the results showed that the common causes of disputes in modular projects include: (1) delays in work progress, (2) lack of team spirit, and (3) lack of communication. Based on that, the analysis of dispute causation network show that the lack of contractual terms promoting efficient communication and collaboration in the project is considered as one of the primary contractual risks in modular construction projects. Ultimately, this paper adds to the body of knowledge by helping practitioners in better understanding the risk and causal factors that should be addressed to minimize disputes in modular construction projects. Future research works could focus on comparing the differences in the driving causes of disputes between modular construction projects and traditional stick-built construction projects. Furthermore, a comparison can be done to identify whether the project delivery methods adopted in modular construction projects affect the root causal mechanisms of disputes and conflicts.

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Opportunities and Challenges of Offsite Construction

R. Assaad, I. H. El-adaway, M. Hastak, and K. LaScola Needy

1 Introduction

Although the construction industry is considered a substantial contributor and driver of the US economy [4], this industry has experienced a slow increase in its overall productivity when compared to other sectors [24]. For example, the productivity in the manufacturing sector has doubled during the previous decades while the construction productivity has remained flat during the same period [10]. Coupled with low productivity levels, the construction industry is facing considerable challenges due to shortages in skilled labor which became more pronounced after the Great Recession of 2007–2009 [13]. This is reflected by the fact that around 2.3 million construction employees were displaced after the Great recession, which constitutes around 30% of the workforce [22, 33]. This has led many construction projects to experience substantial cost and schedule overruns [5]. To this end, companies in the construction industry have shifted their attention to the use of manufacturing techniques and processes, such as offsite construction, to address the challenges of poor productivity, shortage of skilled labor, and unsatisfactory project performance [8, 24]. In other words, offsite construction showed great potential to deal with the industry's epidemic problems [3].

Offsite construction—also referred to as offsite manufacturing, modular construction, or industrialization—is one of the most prominent disruptions experienced by the industry [35]. Offsite construction could be defined as "the technique of

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exporting a portion of site-based work to off-site, such as at fabrication/modular assembly shops or yards" [11]. That said, offsite construction includes different activities, being prefabrication of parts, sections, or entire units called modules, in factory-controlled environments [9]. As such, the term offsite construction in this paper is utilized to indicate the construction technique that employs prefabrication, preassembly, and modularization, rather than any specific type of two-dimensional (2D) or three-dimensional (3D) units or components. In fact, offsite construction is considered as the construction equivalent of assembly-line production which is seen in the manufacturing sector [23].

The use of offsite construction technology and method is perceived to substantially increase and gain rapid attention in the short- and long-term [20]. This is reflected by a study conducted by Market Research Future [25] which predicts that the market for offsite/modular construction will flourish with a compound annual growth rate of 5.95% and a global market value of $154.8 million by the end of the forecast period (i.e. 2026). In addition, following the Asia–Pacific region, the North America area is the second largest region for offsite/modular construction with a market share of 27.6% and a market value of $28.7 million [18]. While multiple research efforts have been directed to examine different characteristics of offsite construction, very little research studies were directed to study the workforce-related aspects of offsite construction.

2 Goal and Objectives

The goal of this study is to investigate the implications of offsite construction on the workforce. In relation to that, the associated objectives include: (1) identification of the different offsite construction workforce properties relevant to offsite construction; (2) quantification of the impacts of offsite construction on the identified offsite construction workforce properties; and (3) examination of the different opportunities and challenges of offsite construction in relation to the workforce. To this end, this study helps practitioners in better understanding and realizing the implications of offsite construction as related to the key workforce opportunities and challenges; which would ultimately help in having better performance of the offsite construction operations.

3 Previous Studies and Knowledge Gap

Many studies have been conducted to examine and investigate different characteristics of offsite construction. In relation to that, this section provides a review of previous related studies and identifies the knowledge gap that this paper aims to address.

3.1 Existing Offsite Construction Related Research Efforts

Many research efforts were directed to study multiple aspects of offsite construction. In relation to that, Ahn et al. [2] conducted a comparison of worker safety risks between offsite construction and onsite methods to provide an empirical, evidence-based explanation for why offsite construction can help reduce safety risks on construction sites. Nasirian et al. [27] used optimization and multicriteria decision-making techniques to compare the performance measures associated with different labor skill sets, and they helped industry practitioners in workforce planning and managing offsite construction by quantifying how performance measures and labor skill sets interact with each other. Tai et al. [34] determined the worker training time for precast component production (a type of offsite construction) in construction, and they developed a learning curve model for workers to master the manufacture of precast components. Duncheva and Bradley [15] provided a multifaceted productivity comparison of offsite timber manufacturing strategies between the Mainland Europe (EU) and the United Kingdom (UK), and they found that the labor productivity of the surveyed UK panelized and EU volumetric manufacturers was comparable but the UK volumetric manufacturers' productivity was lower. Hanna et al. [19] provided a state of prefabrication practice in the electrical construction industry, and they provided that prefabrication users are planning to invest more effort in improving prefabrication practices within their companies by developing training programs for personnel and establishing protocols for working with suppliers and vendors.

On the other hand, Nahmens and Ikuma [26] studied the effects of lean construction on the sustainability of modular homebuilding, and they showcased how to address the barriers to the widespread application of sustainable homebuilding (e.g., higher initial costs largely attributable to the learning curve of workers building with these practical innovations and technologies and the added cost resulting from ill-defined construction processes). Said [31] modeled and predicted the likelihood of prefabrication feasibility for electrical construction firms, and the study found that prefabrication feasibility is significantly dependent on (1) four industry-related determinants: regional economic growth, industry competition, labor cost rate, and worker union resistance, and (2) two main internal firm-related determinants: building information modeling (BIM) capability and supply coordination with vendors. Ramaji et al. [30] presented a delivery framework for multi story modular buildings that can address both the project-based and product-based nature of these buildings, and they outlined a baseline to extend the industry foundation classes (IFC) data schema and enable it to model specific elements of modular buildings. Abdul Nabi and El-adaway [1] determined the decision-making factors that affect the use of offsite construction based on a comprehensive review of the literature, and they found that a total of 50 factors impact the various modular construction operations in the construction industry. Assaad et al. [7] studied the commercial and legal considerations of offsite construction projects and their hybrid transactions, and they offered guidance to the management, commercial, and legal practitioners on different aspects related to offsite construction transactions. O'Connor et al. [28] determined the changes needed in current engineering, procurement, and construction processes to create optimal environment for a broader and more effective use of modularization, and they found that project teams shall pay close attention to module envelope limitations, team agreement on project drivers, adequate owner-planning resources and processes, timely freeze of scoping and design, and due recognition of possible early completion from modularization.

Furthermore, Choi et al. [12] investigated the combinatorial effects of modularization critical success factors on the cost and schedule performances of industrial modular projects, and they proposed a conceptual model of cost and schedule. Zhang et al. [36] explored the feasibility, challenges, and critical success factors of modular integrated construction, and they proposed a feasibility index that employs the performance levels and that aggregates global weights of critical success factors to evaluate the feasibility of modular integrated construction projects. Enshassi et al. [16] introduced a methodology that employs Bayesian inference theory for the dynamic assessment and proactive management of excessive geometric variability issues in modular construction projects. O'Connor et al. [29] addressed a leveraging opportunity for modularization augmentation by examining how modularization and design standardization relate to one another in the industrial sector, and they provided insights into the characteristics of modular projects with standard design, assessment of its impact and benefits, and lessons learned.

3.2 Knowledge Gap

Based on the extensive literature review of previous research studies on offsite/modular construction, it could be concluded that multiple research efforts have been directed to examine different characteristics of offsite construction. In addition, little research studies were directed to study the workforce-related aspects of offsite construction. Moreover, the previous studies that investigated labor-related characteristics mainly focused on one certain aspect (such as productivity, skillset, training, safety considerations, etc.). To this end, there is a knowledge gap in the current body of knowledge as related to understanding the implications of offsite construction on multiple, rather than specific, workforce-related aspects and properties. That said, this paper aims to address this critical research need and knowledge gap through a research methodology which consists of the interrelated review of previous studies (to identify the key workforce properties) as well as the analysis of industry experts' opinions (to quantify the impacts of offsite construction).

4 Methodology

The authors followed a research methodology comprising multiple steps as presented in Fig. 1. Details on each one of the followed methodology steps are presented in the next subsections.

4.1 Identification of Workforce Properties

The authors performed a literature review of previous studies to identify the workforce properties of interest, which will need to be included in the survey distributed to construction experts. Limited by the length of this paper, it is not possible to list all the studies that were reviewed to determine the workforce properties. In relation to that, Table 1 shows the final outcome of the performed literature review which identified a total of 23 workforce properties.

After the identification of the different workforce properties of interest, a survey was developed and distributed to industry experts. Details related to the survey design and dissemination are shown in the next subsections.

4.2 Survey Development

As far as survey development is concerned, and upon identifying the workforce properties of interest shown in Table 1, the authors developed a survey to quantify the level of opportunity or challenge of each one of these workforce properties. As

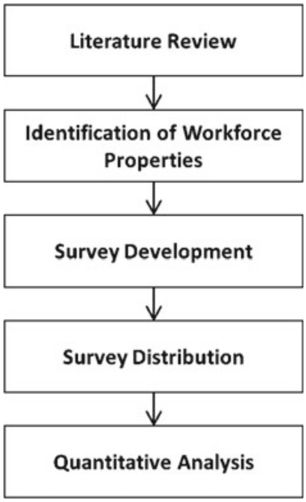

Fig. 1 Research methodology

Table 1 Identified workforce properties

Workforce properties
Workforce productivity
Workforce rework (man-hours attributed to rework)
Idle (stand-by) workforce
Labor disputes
Labor theft and fraud
Workforce (or staffing) turnover
Workforce mobility, transfer, or relocation
Workforce overtime
Quality of the working conditions
Workforce health and safety
Workforce absenteeism
Workforce fatigue
Age of retirement
Crew or team size
Job security
Workforce's quality of work
Workforce compensation
Length of workforce career path progression
Workforce learning rate
Travel and per diem rate
Workforce smartness or flexibility
Cost of workforce training and development
Shifting work hours to international low-cost labor locations

such, a survey was developed to allow the respondents to rate each of the identified 23 workforce properties. In relation to that, there is a need to define a unified scale for all respondents in order to ensure better understanding and consistency among respondents. To this end, the authors adopted a double sided 5-point Likert scale where a positive score means an increase and a negative score means a decrease as shown in Table 2. It is worth mentioning that the used Likert scale in this paper is adopted from the Standard Likert Scale proposed by the Construction Industry Institute (CII) [21], and which has been used in multiple studies. Also, the respondents had the option to select 'no change' if they perceive that there will be no change in the associated workforce property.

Table 2 Used likert scale

Description of the scale	Associated range
±1 = Negligible*	Will change by <5%
±2 = Minor*	Will change by 5–10%
±3 = Moderate*	Will change by 10–20%
±4 = Significant*	Will change by 20–50%
±5 = Extreme*	Will change by >50%

* A positive sign means increase and a negative sign means decrease

4.3 Survey Distribution

As far as survey distribution is concerned, the survey was distributed and developed through Qualtrics which is a cloud-based platform used to create and distribute web-based surveys. Qualtrics is widely used for academic research due to its exceptional abilities of having a large array of question types, possessing highly customizable survey designs and appearances, and allowing for complex experimental designs and user-tailored survey paths.

The authors sent the survey to targeted industry professionals representing major stakeholders in offsite construction. In relation to that, the targeted respondents were industry experts: (1) having experience with the US construction industry, (2) having experience with either the craft workforce, with the integration and usage of construction technologies, and/or with offsite construction; (3) representing one of the central project stakeholders: (a) owners or developers; (b) architects, engineers, or service providers; and (c) contractors, construction managers; or fabricators; (4) representing one of the key industry sectors: (i) building and commercial; (ii) industrial; and (iii) infrastructure; and (5) affiliated directly or indirectly with CII member companies. It is to be noted that this research is carried out collaboratively by the authors through funding provided by CII under RT-371 research team.

4.4 Quantitative Analysis

After developing and distributing the survey, a quantitative analysis of the obtained results was performed using descriptive statistics. In relation to that, the average value of all obtained responses for each one of the identified workforce properties was calculated. It is worth mentioning that the quantitative analysis, represented by the average value, was reported for each one of the three sectors: industrial, building and commercial, and infrastructure. This is performed to be able to compare whether these three sectors agree or disagree on the opportunities and challenges of offsite construction as related to the labor properties.

5 Results

This section presents the obtained results of the collected data from the industry experts. It is worth mentioning that this paper shows the initial analysis and preliminary results obtained from the survey since the research efforts of CII's RT-371 research team are still ongoing.

5.1 Respondents Characteristics

This section aims to provide the demographics of the industry experts who provided their input to this research. In relation to this, the results and analysis of the survey are based on a total of 45 responses. To assess the sufficiency of the obtained total number of responses, it was compared to recommendations from previous commonly used references. In relation to that, different studies suggested the minimum sample sizes used for survey-based to be: (1) between 15 and 35 respondents [17]; (2) between 30 and 50 respondents [32], and (3) between 25 and 75 respondents [14]. To this end, the obtained responses from 45 industry experts fall within the most common ranges used in survey-based research studies. Thus, it could be concluded that the obtained responses are sufficient enough to provide robust analysis and conclusions.

The average industry experience of the respondents is 27.93 years, and they have an average experience of 14.87 years with offsite construction in specific. In addition, the industry professionals represent one of the central project stakeholders: (1) owners or developers; (2) architects, engineers, or service providers; and (3) contractors, construction managers; or fabricators. Also, the industry professionals representing one of the key industry sectors: (1) building and commercial; (2) industrial; and (3) infrastructure.

5.2 Quantitative Survey Analysis

Table 3 shows the obtained results from the distributed survey based on the collected input from 45 industry experts.

As detailed in the methodology section, a positive value in Table 3 indicates that the respondents perceive that the associated workforce property will have an increased change, whereas a negative value in Table 3 reflects that the respondents perceive that the associated workforce property will have a decreased change. An in-depth analysis and discussion of the obtained results are presented in the next section.

Table 3 Obtained results from the survey

Workforce properties	Industrial sector (mean)	Building and commercial sector (mean)	Infrastructure sector (mean)
Workforce productivity	1.5	2.2	3.0
Workforce rework (man-hours attributed to rework)	0.0	−1.13	−1.0
Idle (stand-by) workforce	−0.54	−1.2	−1.67
Labor disputes	0.17	−0.4	0.17
Labor theft and fraud	0.0	−0.93	0.5
Workforce (or staffing) turnover	0.21	−0.27	0.17
Workforce mobility, transfer, or relocation	−0.04	−0.67	−1.17
Workforce overtime	0.33	−0.07	0.0
Quality of the working conditions	1.17	2.27	2.0
Workforce health and safety	1.54	2.13	2.5
Workforce absenteeism	0.29	−0.53	−1.17
Workforce fatigue	0.17	−0.53	−1.33
Age of retirement	1.12	1.53	1.67
Crew or team size	−0.38	−0.87	−0.5
Job security	−0.12	0.53	2.0
Workforce's quality of work	0.83	1.47	2.33
Workforce compensation	0.29	0.53	0.83
Length of workforce career path progression	0.5	0.73	0.83
Workforce learning rate	0.25	0.07	0.0
Travel and per diem rate	0.88	1.2	0.83
Workforce smartness or flexibility	0.92	1.4	2.17
Cost of workforce training and development	1.29	0.87	0.5
Shifting work hours to international low-cost labor locations	1.75	1.0	0.67

6 Analysis and Discussion

This section aims to provide an in-depth discussion and analysis of the obtained results. Table 3 reflects that there is agreement between the three industry sectors on most of the workforce properties (i.e. 16 out of the 23 properties—around 70%—have the same sign, being positive or negative, across all considered sectors). However, 7 out of the 23 properties (around 30%) were viewed differently among at least one of the three sectors. It is worth mentioning that this paper analyses and discusses only the initial and preliminary results obtained from the survey since the research efforts of CII's RT-371 research team are still ongoing.

Starting with the workforce properties that all three industry sectors had agreement on, it could be noted that one of the opportunities for the offsite construction workforce is an increased productivity. This could be attributed to the fact that the workers are performing the tasks in a more controlled environment which is considered to be a more efficient workplace. For the second opportunity, the results reflected that the manhours attributed to rework are reduced when work is performed offsite, which is considered to be an opportunity for the workforce because it helps in accomplishing the tasks from the first time instead of doing them more than once. In addition, offsite construction is perceived to decrease the percentage of idle workforce (i.e. the stand-by workers that are not doing any actual work), which is an opportunity because it ensures a better workforce utilization rate. For workforce mobility, all the considered sectors perceived that it would decrease due to offsite construction, which could be viewed either as opportunity (e.g. for older workers or for workers who have family) or as a challenge (for younger workers who tend to appreciate traveling and exploring different geographical areas); however, this might not be universal. All three sectors also perceive that another opportunity is the increase in the quality of the workforce's working conditions which would be attributed to the controlled environment. In addition, there is an agreement that another opportunity is improvement in workforce's safety and health which could be related to the fact that the offsite construction activities are performed in an offsite facility shop, and thus the management of the workforce and of the different variables affecting the works is easier. For the age of retirement, there is an agreement that the workforce will be able to work for a longer period before retiring which could be related to the fact that offsite construction does not necessarily require considerable physical efforts as compared to the traditional construction works. While this might be seen as an opportunity for some workforce groups, it might also be considered as a challenge for others. Since offsite construction usually provides that each worker (or certain workers) to be responsible for the operation of certain equipment or for performing certain activity or task, all three considered sectors perceive that the team or crew size will decrease due to offsite construction. While this might be seen as an opportunity for some workforce groups, it might also be considered as a challenge for others. Another opportunity is enhanced workforce's quality of work which could be, more or less, related to the perceived improvements in the working conditions and the workforce' health and safety considerations as well as to the decrease in rework. Since offsite construction usually necessitates the traditional workforce to learn manufacturing-related skills, all three considered sectors perceive that offsite construction would increase the workforce compensation (which is considered to be an opportunity for the workforce) for the additional learned skills such as BIM that is experiencing substantial development and use in the construction industry [6]. One challenge faced by the workforce is the increase in the length of workforce career path progression as perceived by the survey results. On the other hand, an additional opportunity is the increase in the workforce's learning rate which means that offsite construction can make the workforce learn the skills and activities faster. Another opportunity is the increase in the travel and per diem rate for the offsite construction workforce. Moreover, the three considered sectors perceive that the workforce smartness and flexibility would increase if the work is performed in an offsite construction facility. For other challenges, it is perceived that the cost of workforce training and development would increase and that shifting work hours to international low-cost labor locations would also increase which causes displacement of the local workers.

Moving to the analysis and discussion of the workforce properties that were viewed differently by at least one of the three considered sectors, the building and commercial sector perceives that labor disputes would decrease (which is an opportunity) but the industrial and infrastructure sectors both perceive that labor disputes would increase (which is a challenge). The building and commercial sector also perceives that labor theft and fraud would decrease (which is an opportunity) but the infrastructure sector perceives that labor theft and fraud would increase (which is a challenge), while the industrial sector does not see it to either increase or decrease. Similarly, the building and commercial sector perceives that the labor turnover will decrease while the industrial and infrastructure sectors both perceive that labor turnover will increase. In addition, the building and commercial sector perceives that workforce overtime will decrease (which is generally seen as opportunity if it is performed in an excessive way) but the industrial sector perceives the workforce overtime to increase (which is generally seen as a challenge if it is performed in an excessive way) while the infrastructure sector does not see it to either increase or decrease. For the workforce absenteeism, the infrastructure and building and commercial sectors both perceive it to decrease (which is an opportunity) while the industrial sector perceives it to increase (which is a challenge). Similarly, for the workforce fatigue, the infrastructure and building and commercial sectors both perceive it to decrease (which is an opportunity) while the industrial sector perceives it to increase (which is a challenge). Finally, for the job security, the infrastructure and building and commercial sectors both perceive it to be enhanced (which is an opportunity) while the industrial sector perceives it otherwise (which is a challenge).

7 Conclusion and Future Work

Companies in the construction industry have shifted their attention to the use of manufacturing techniques and processes, such as offsite construction technologies and methods, to address the challenges of poor productivity, shortage of skilled labor, unsatisfactory project performance, among other issues. In fact, offsite construction showed great potential to deal with the industry's epidemic problems. While different studies have been conducted to investigate multiple characteristics of offsite construction, there is still a lack of research that was directed to study the opportunities and challenges of offsite construction for the workforce. As such, the goal of this study is to investigate the implications of offsite construction on the workforce. In relation to that, the associated objectives include: (1) identification of the different offsite construction workforce properties relevant to offsite construction; (2) quantification of the impacts of offsite construction on the identified offsite construction workforce properties; and (3) examination of the different opportunities and challenges of offsite construction in relation to the workforce. The findings reflected that offsite construction could create: (1) many opportunities for the workforce including greater productivity, higher learning rate, better working conditions, enhanced worker quality, and improved safety and health, among others, and (2) some challenges for the workforce including longer career path progression, higher cost of training and development, and displacement of local workers, among others. This study helps practitioners in better understanding and realizing the implications of offsite construction as related to the key workforce opportunities and challenges; which would ultimately help in having better performance of the offsite construction operations. Future research work could include providing an analysis of the impact of offsite construction on the workforce occupations as well as identifying and studying the offsite characteristics and technologies that the workforce needs to learn for a better leverage of offsite construction.

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Prioritization of Project Factors Affecting the Use of Modular Construction: Comparison Between the Perspectives of Industry and Literature

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1 Introduction

Modular construction methods have been proposed as a solution to the poor productivity and lack of skilled labors witnessed in the construction industry [11]. In fact, the modular approach is perceived to result in increased cost and schedule predictability, improved safety, and enhanced environmental performance [15]. In addition to that, the evolution of advanced information and manufacturing technologies have further favored the use of modular approach in the industry [3, 24]. As such, it is expected to have such increased interest towards modular construction methods by industry practitioners and stakeholders to improve the performance of construction projects. Furthermore, modular construction methods are perceived to vary from the traditional construction methods in many aspects, particularly as related to the need for more complex transportation, design, engineering, and planning requirements [5, 16, 18]. For that reason, there is a need to develop updated decision-making models and procurement processes for the project stakeholders to break out the antiquated traditional stick-built methods. To that respect, many research efforts have been directed to investigate the modular approach and its operations in the construction market [1].

Furthermore, it is evident that the attention of the construction industry and academic community has been remarkably directed towards modular construction methods during recent years. In fact, a collaboration between industry and academia is believed to leverage the use of modular approach in the construction industry [13]. However, industry and academia are generally perceived to have a difference in their mindset [10] leading to inefficient collaboration and communication between them [17]. As such, it is important to align research work with industry needs in order to maximize associated benefits and promote knowledge advancement as related

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to modular construction. While many research works have addressed the modular approach in the industry, the alignment of the literature studies with the industry's perception as related to the project factors impacting modular construction remains uninvestigated.

2 Goals and Objectives

The goal of this paper is to perform a comparison between industry and literature as related to the prioritization of project factors affecting the use of modular construction. To this end, the papers' objectives are to: (1) identify a comprehensive list of factors affecting the use of modular construction based on an extensive review of the literature; (2) quantify the importance of the identified project factors as perceived by the literature; and (3) consequently examine the industry's perspective and opinion. Ultimately, a comparison between the perspective of the literature and the industry is conducted to examine their alignment as related to the project factors impacting modular construction operations and processes.

3 Modular Construction Research Trends

Existing research efforts have addressed modular construction and its operations in the market either qualitatively or quantitatively. Qualitative research efforts have focused on identifying the drivers and barriers to the use of modular construction in various geographical markets and construction sectors. For instance, Nadim and Goulding [14] investigated the factors affecting the adoption and failure of offsite construction in the United Kingdom. Another example is the work of O'Connor et al. [15] who established a critical success factors for modular construction projects. On the other hand, quantitative research efforts have developed models or decision support tools addressing various modular construction operations and processes. According to Abdul Nabi and El-adaway [1], the models developed in the literature have been mainly developed to cover modular construction decisions, operations, and processes as related to scheduling and planning, design configuration, modular feasibility and selection of construction method, overall project performance, risk assessment, supply chain and modular construction market. For instance, Li et al. [12] established a simulation model to examine the impact of lean construction methods and information technology on the performance of prefabricated residential projects. Enshassi et al. [6] developed systematic risk-based approach to manage the unique modular risks in construction projects. Another example is the work of Rausch et al. [19] who provided a model that optimizes the assembly planning of modules as to minimize rework and risks associated with restricted tolerances. Furthermore, Isaac et al. [8] developed a method to optimize modular configuration of building design. In addition, Choi et al. [5] established a business case model to optimize the proportion of work hours to be shifted offsite. To this end, academic community attention has been remarkably increased towards modeling and examining modular construction processes and operations in the industry.

4 Research Methodology

This section provides all details related to the followed methodology.

4.1 Analysis of the Literature Perspective

In this section, the authors aim to establish a list of project decision-making factors affecting modularization in the construction industry and consequently to calculate their frequency of occurrence in the literature. The different steps followed as related to the analysis of the literature are present in the next subsections.

4.1.1 Collection of Journal Papers

The reviewed journal papers were retrieved based on the following methodology: (1) "Scopus" was adopted as the database search engine in this research; (2) Pre-determined keywords were used including modular, modularization, pre-fabrication, offsite, pre-assembly, among others; (3) a preliminary abstract and title screening was performed to examine whether the collected papers fall within the scope of this research or not; and then (4) full paper assessment and analysis was conducted to the remaining journal papers. Based on the aforementioned methodology, 65 journal papers were reviewed. These selected journal papers addressed modularization either qualitatively (i.e. the use of modularization in the industry) or quantitatively (i.e. development of models, decision making tools, etc.). After analyzing the 65 journal papers, the authors established a comprehensive list of 50 project factors affecting modularization in the construction industry. The identified list is shown in the 'Results and Analysis' section.

4.1.2 Construction of the Reference Matrix

After identifying the project factors, the authors constructed a reference matrix to count the frequency of occurrence of each identified factor in the literature. The reference matrix represents the identified project factors as rows and the reviewed papers as columns. Whenever a factor is addressed or referred to in a paper, a value of 1 is inserted into its corresponding cell; otherwise, the cell would take a value of 0. Figure 1 presents an illustrative example of a reference matrix. As shown in the

Fig. 1 Illustration of the reference matrix

	Paper i	*Paper i+1*	*Paper i+2*	...	*Paper I*
F_1	1	1	0	..	1
F_2	0	1	0	...	1
...	1	0	1	...	1
F_n	0	0	1	...	1

figure, paper $i + 1$ addresses factors F_1 and F_2 since the corresponding cells have a value of 1 while a value of 0 is assigned for the other cells.

4.1.3 Quantitative Analysis of the Literature

After constructing the reference matrix, a score is calculated for each identified project factor by adding all corresponding cells in each row using Eq. 1. For instance, a score of 9 for a project factor F_i reflects that such factor has been addressed in 9 of the investigated papers and suggested to impact modularization in the construction industry.

$$\mathrm{Score_i} = \sum_{\text{x= first paper in the matrix}}^{\text{last paper in the matrix}} \mathrm{C_{i,x}} \tag{1}$$

where $\mathrm{C_{i,x}}$ is the value of the cell associated with a project factor F_i in paper number x in the reference matrix.

Afterwards, the project factors were ranked based on the calculated scores. The ranking was conducted in a descending order where the factor with the highest score is ranked as 1, and so on. Since rank normalization enables the comparison of datasets retrieved from different sources or platforms [23], the authors normalized the obtained ranks. This shall ensure reliable conclusions and accurate comparison between the literature and industry. To this end, the authors used the rank sum weighting method established by StillWell et al. [22] where the weights are computed as the normalized individual ranks of variables. Therefore, the ranks were normalized using Eq. 2.

$$\mathrm{weight_i} = \frac{N - R_i + 1}{\sum_{i=1}^{N} N - R_i + 1} \tag{2}$$

where $\mathrm{weight_i}$ is the importance weight of project factor F_i as perceived by the literature; N is the total number of project factors, which is 50; R_i is the ranking assigned to a project factor F_i.

4.2 Analysis of the Industry Perspective

This section provides all details needed as related to the followed steps for the analysis of the industry perspective in relation to the identified 50 project factors.

4.2.1 Survey Design and Distribution

An online survey was developed using Qualtrics. The survey was composed of two sections. The first section required the respondents to input their demographic data. As for the second section, the respondents were asked to rate the importance of each project factor on a 7-point Likert scale (1: Extremely Unimportant, 2: Very Unimportant, 3: Little Unimportance, 4: Neutral, 5: Little Importance, 6: Very Important, 7: Extremely Important). The authors adopted a 7-point Likert scale as it minimizes ambiguity [4] and promotes an easier quantitative judgment by the respondents [7].

After developing the survey, the authors collected a total of 30 responses from industry experts having managerial and strategic job positions in the US construction industry. While the average construction experience of respondents is 27.9 years, their average experience in modularization is 14.56 years. As such, the retrieved responses represent a wide range of experience in the US construction market on one hand, and modular construction market on the other hand. Therefore, the collected data can be considered a good representative of the US modular construction industry.

4.2.2 Quantitative Analysis of the Industry Perspective

As provided earlier, this paper aims to compare the project factors' importance obtained from literature (i.e. frequency analysis) with those obtained from the industry (i.e. survey). Thus, the importance for each factor needs to be also quantified using the data collected from the industry responses. To that respect, the mean importance score of each project factor is calculated. Then, the factors are ranked based on their obtained mean importance scores. Following the same approach adopted for the ranks obtained from the literature, the authors normalized the ranks obtained from the industry as shown in Eq. (2).

4.3 Comparison Between Industry and Literature

This section provides all details needed as related to the followed steps for the comparison of the scores obtained from industry experts and from literature analysis.

4.3.1 Kendall's Concordance Analysis

Kendall's Concordance analysis was conducted to examine alignment between the ranks obtained from the literature and industry [21]. The corresponding null hypothesis is that the rankings of project factors of the literature and industry are unassociated. As such, the conducted test will highlight whether there is enough evidence to conclude significant discordance between literature and industry's perspective as related to the importance of the project factors. For this test, the authors adopted the most used significance level as a decision boundary for this test, which is 5%. Furthermore, this statistical technique generates a coefficient called Kendall's coefficient of concordance (w). This coefficient reflects the extent of agreement or concordance between two or more distinct groups [21]. While having w equivalent to 1 indicates a perfect agreement, having w equal to 0 indicates no agreement between the literature and industry.

4.3.2 Quantification of the Gap Difference Between Literature and Industry

To examine misalignment between the literature and industry perspectives, the difference between the normalized ranks (weights) obtained from the literature and survey was calculated for each project factor. Ultimately, this shall help in identifying the gap between the existing literature work and industry needs. The difference in the weights is computed using Eq. 3.

$$D_i = \frac{\text{Industry Weight}_\text{i} - \text{Literature Weight}_\text{i}}{\text{Industry Weight}_\text{i}} \times 100 \tag{3}$$

where D_i is the percentage gap difference in the weights computed for a project factor F_i.

5 Results and Analysis

This section presents and analyzes the obtained results.

5.1 Quantitative Analysis of the Literature's and Industry's Perspective

Based on the conducted literature analysis, a total of 50 project factors we identified where these factors affect the use of modular construction in the industry. The identified factors include various aspects related to cost and profitability, time, quality, safety, design and engineering, resources and technology, regulatory and organizational structure, and sustainability. The identified project factors are shown in Table 1 (Second Column).

Afterwards, the authors calculated a score for each project factor using Eq. 1. Based on the calculated scores, the factors were ranked as to reflect their importance according to the literature perspective. The ranks were then normalized using the rank sum weighting method, particularly Eq. 2. A similar approach was conducted to quantify the industry perspective as related to the identified project factors. However, the ranking of the industry perspective was conducted based on the mean importance scores obtained from the collected survey data. The results of the quantitative analysis for the literature and industry are shown above in Table 1. As reflected in the table, the top important factors according to the literature are: F38 (Productivity), F28 (Environmental impact), F44 (Availability of experienced and skilled labors), F32 (Standardization), and F29 (Material and construction waste management). On the other hand, the top important factors according to the industry are: F24 (On-site safety performance), F12 (Activity sequencing), F38 (Productivity), F13 (Site disruptions and delays), F23 (Quality of prefabricated components/modules).

5.2 Kendall's Concordance Analysis

To statistically examine the degree of agreement between the literature and industry, the authors conducted Kendall's concordance analysis using Python programming language. The conducted Kendall's concordance analysis resulted in a coefficient equal to 0.126 indicating a very weak agreement between the literature and industry when it comes to the ranking of the project factors. The test also generated a *p*-value of 0.208. That said, the null hypothesis fails to be rejected at a significance level equal to 0.05. Therefore, there is a sufficient evidence that the rankings of the literature and industry are unassociated. The conducted test substantiates the misalignment of the literature perspective with that of the industry. Ultimately, the variations in the rankings indicates a difference in the mindset between industry and academia.

Table 1 Results of the quantitative analysis

Code	Project Factors	Literature		Industry	
		Rank	Weight	Rank	Weight
F1	Direct labor costs	9	0.0227	7	0.0250
F2	Overhead costs	17	0.0184	22	0.0165
F3	Supervision costs	22	0.0157	22	0.0165
F4	Transportation costs	10	0.0222	8	0.0245
F5	Initial (capital) costs	10	0.0222	17	0.0194
F6	Installation & assembly costs	18	0.0178	6	0.0256
F7	Crane & equipment costs	16	0.0189	17	0.0194
F8	Design & engineering costs	24	0.0146	24	0.0154
F9	Material costs	16	0.0189	26	0.0142
F10	Speed of return on investment and profitability	13	0.0205	18	0.0188
F11	Economy of scale	20	0.0168	18	0.0188
F12	Activity sequencing	15	0.0195	2	0.0279
F13	Site disruptions & delays	17	0.0184	4	0.0268
F14	Climate dependency	15	0.0195	23	0.0159
F15	Design & engineering lead time	19	0.0173	21	0.0171
F16	Transportation lead times	21	0.0162	19	0.0182
F17	Commissioning and Testing	26	0.0135	30	0.0120
F18	Quality control implementation	9	0.0227	8	0.0245
F19	Inspection at manufacturing plant	19	0.0173	11	0.0228
F20	Rework	19	0.0173	15	0.0205
F21	Capacity & experience of manufacturer/supplier	14	0.0200	8	0.0245
F22	Aesthetic	18	0.0178	28	0.0131
F23	Quality of prefabricated components/modules	23	0.0151	5	0.0262
F24	Onsite safety performance	17	0.0184	1	0.0285
F25	Workplace congestion	14	0.0200	17	0.0194
F26	Exposure to hazards	19	0.0173	12	0.0222
F27	Safety planning & communication	25	0.0141	7	0.0250
F28	Environmental impact	2	0.0265	27	0.0137
F29	Material & construction waste management	4	0.0254	24	0.0154

(continued)

Table 1 (continued)

Code	Project Factors	Literature		Industry	
		Rank	Weight	Rank	Weight
F30	Energy efficiency	19	0.0173	25	0.0148
F31	Green practices	24	0.0146	31	0.0114
F32	Standardization	3	0.0259	10	0.0233
F33	Design flexibility & changes	8	0.0232	9	0.0239
F34	Design freeze implementation	18	0.0178	21	0.0171
F35	Technical & design feasibility	10	0.0222	16	0.0199
F36	Use of repetitive design	12	0.0211	20	0.0176
F37	Tolerance & interfacing considerations	11	0.0216	12	0.0222
F38	Productivity	1	0.0270	3	0.0273
F39	Use of modern technologies	7	0.0238	17	0.0194
F40	Efficiency & capacity of handling & lifting equipment	5	0.0249	13	0.0216
F41	Efficiency & capacity of transportation modes/infrastructure	4	0.0254	21	0.0171
F42	Site attributes & logistics	7	0.0238	12	0.0222
F43	Previous experience	13	0.0205	8	0.0245
F44	Availability of experienced & skilled labors	2	0.0265	10	0.0233
F45	Cultural perspective	9	0.0227	29	0.0125
F46	Collaborative and coordinative planning	5	0.0249	14	0.0211
F47	Contractual conditions and considerations	18	0.0178	15	0.0205
F48	Project delivery method	23	0.0151	14	0.0211
F49	Legal & regulatory considerations	6	0.0243	23	0.0159
F50	Project & operational permit issues	24	0.0146	23	0.0159

5.3 *Identification of Misalignment Between Literature and Industry*

To better examine the differences and similarities between the literature and industry, the authors plotted the obtained weights for each project factor as shown in Fig. 2. For instance, some factors have industry weights much higher than those obtained from the literature such as F12 (Activity sequencing) and F13 (Site disruptions and

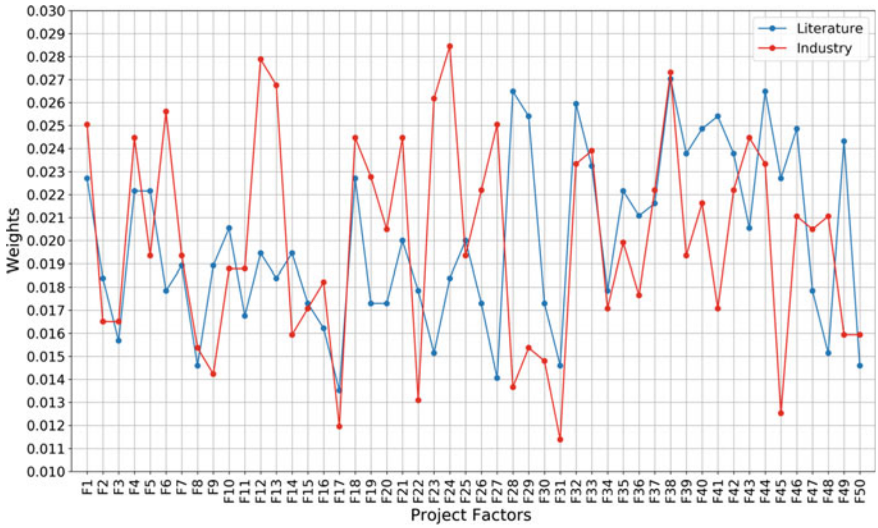

Fig. 2 Comparison between the weights obtained from the literature and industry

delays). On the other hand, some factors possess industry weights much lower than those obtained from the literature such as F28 (Environmental Impact) and F45 (cultural perspective). Also, it can be noted from Fig. 2 that there is alignment (the difference between the weights is very close to zero in Fig. 2) between industry and literature as related to some of the project factors including F7 (Crane and equipment costs), F15 (Design and engineering lead time), F25 (Workplace congestion), F33 (Design flexibility and changes), among others.

As discussed in the methodology section, the authors quantified the misalignment between literature and industry as related to each factor using Eq. 3. The computed gap (D_i) reflects the relative percentage difference between the weights obtained from the literature and the industry for a given project factor F_i. In fact, such quantification allows the authors to identify the gap between industry needs and the research work efforts. Figure 3 shows the percentage gap difference between industry and literature.

As shown in Fig. 3, the percentage difference can be either positive or negative. While a positive percentage difference reflects that the factor has been understudied in the literature as compared to its industry importance, a negative percentage difference reflects that the factor has been overstudied in the literature as compared to its industry importance. Consequently, a percentage difference close to zero indicates that the factor has been addressed in the literature to the same importance level perceived by the industry. For this study, the authors will assume a threshold of 30% to identify gap between industry and literature. In other words, the project factors possessing a percentage difference equal to or greater than 30% are associated with significant gap between industry and literature.

As shown in Fig. 3a, the factors that have been understudied by the literature compared to their industry importance include the following 6 factors: F27 (Safety

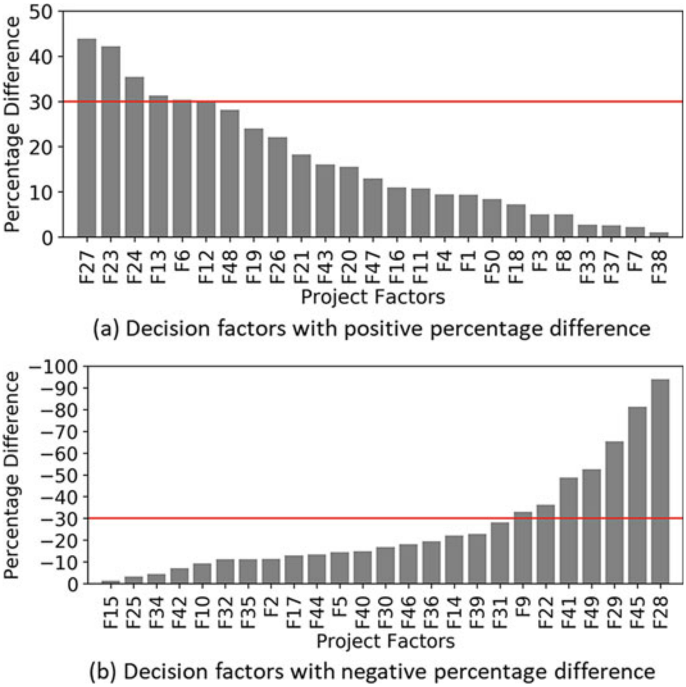

Fig. 3 Percentage gap difference between industry and literature

planning and communication), F23 (Quality of prefabricated components/modules), F25 (Onsite safety performance), F13 (Site disruptions and delays), F6 (Installation and assembly costs), and F12 (Activity sequencing). On the other hand, and as reflected in Fig. 3b, the factors that have been emphasized by the literature but were not found as much important by the industry are the following 7 factors: F28 (Environmental impact), F45 (cultural perspective), F29 (Material and construction waste management), F49 (Legal and regulatory considerations), F41 (Efficiency and capacity of handling and lifting equipment), F22 (Aesthetic), and F9 (Material costs). Finally, the following 4 factors have been emphasized and addressed by the literature to the same importance level perceived by the literature: F7 (Crane and equipment costs), F38 (Productivity), F15 (Design and engineering time), and F25 (workplace congestion).

6 Discussion

Based on the obtained results, the following recommendations are provided to help future research work in directing their efforts towards the industry needs as to maximize benefits and promote knowledge enhancement:

- Researchers are advised to examine in their future works the modular construction aspects related to safety management. This is reflected by having F27 and F25 among the most factors that were understudied by the literature as compared to their industry importance. While F25 refers to the onsite reported incidents, F27 refers to the need for complex safety planning and communication due to the lifting of heavy and large modules. In fact, and despite the improved safety performance associated with modular construction, there are still some associated onsite safety risks related to the heavy crane operations [2].
- Researchers are advised to investigate activity management in modular construction projects. This is reflected by having F13, F6, and F12 among the most factors that were understudied by the literature as compared to their industry importance. F13 refers to disruptions and delays that could be caused by unanticipated work conditions, poor productivity, or increased shut-down times. Furthermore, F6 refers to the costs associated with the assembly, packing, and installation of the prefabricated elements or modules. As for F12, it refers for the efficient coordination between onsite and offsite construction works. In fact, it is perceived that the lack of synchronization between offsite, where the modules are produced, and the construction site can lead to poor modular activity sequencing and consequently extensive site disruptions and delays [9].
- Another modular construction aspect that should be addressed by future work is related to geometric variability and quality control. This is reflected by having F23 as one of the most factors that have been understudied as compared to their industry importance. F23 refers to geometric variabilities that can be caused by temperature shrinkages, transportation, manufacturing, or installation damages. According to Shahtaheri et al. [20], some discrepancies between the precise production tolerances and uncertain/large tolerances can affect the quality of the prefabricated components and modules leading to rework, site disruptions, and delays.
- As for the environmental, regulatory, and organizational aspects, they have been addressed by research work; however, the industry did not consider them as much important. This is reflected by having F28 and F29 with a high negative percentage difference where F28 refers to the extent of air, water, and noise pollution associated with modular construction and F29 refers to the extent of material recycling and disposal during work execution. As for the regulatory and organization aspects, they include factors F45 and F49 where F45 refers to the resistance of change and innovation in the industry and F29 to the availability of codes and standards, government taxes and incentives, and other governmental regulations.

7 Conclusion

This paper prioritized the project factors affecting the use of modular construction from the literature and industry perspectives. Statistical and quantitative analysis have been conducted to compare the alignment between the industry and literature. The statistical analysis substantiated the difference in mindset between the literature and the industry as related to the importance of the identified project factors. Furthermore, the detailed quantitative analysis showed that the industry is more concerned with safety, activity management, geometric variability, and quality management than the literature. On the other hand, the literature has focused on the environmental, regulatory, and organizational aspects of modular construction more than the industry. Thus, this paper adds to the body of knowledge by highlighting the main modular aspects that reflect the important industry needs. Ultimately, addressing the industry needs by future research work shall lead to maximized research benefits and promoted knowledge advancement.

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Role of Transactional Blockchain in Facilitating Procurement in International Construction Projects

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1 Introduction

Blockchain has been emerging in the previous years as an innovative key technology in a the rapidly evolving world of business and finance. Although it may be met with understandable skepticism, it also offers many benefits such as decentralization, security, flexibility, and transparency. The recently booming conversion to online services and banking has promoted the use of blockchain in many sectors including banking, finance, and supply chain.

However, the construction industry is generally considered a very slow field to adopt new technologies and innovations due to many inherent challenges [1]. Blockchain may have significant potential in revolutionizing procurement and supply chain in the construction industry [14]. For example, in 2019, an industrial painting contract was successfully implemented and completed, in Cape Town, South Africa, using blockchain. The project relied on a smart contract management network using blockchain and distributed technology to increase transparency. The purpose of the tool was to facilitate management practices such as smart contract administration, supply chain track-and-trace and condition monitoring, access management, proof of presence, safety and compliance management, milestone monitoring and payment certification [3].

Accordingly, blockchain can be implemented as a secure platform for financial transactions [2]. It can also be applied in the area of supply chain and product tracking [5]. The main advantage of using blockchain is securely track financial transactions all member have committed that lead to the current state of each asset [19]. However, there are many speculations concerning the implementation of blockchain technology in the construction industry, especially considering the inherent unique challenges in

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construction [14]. This research intends to fill that knowledge gap by investigating the integration of blockchain in the construction industry.

2 Goal and Objectives

The goal of this paper is to provide a holistic understanding of the role of blockchain in facilitating procurement in construction projects, with a focus on international projects. This goal is reached through achieving the following objectives: (1) study the applications of blockchain in the construction industry; (2) investigate current implementations of such applications in construction projects through the analysis of blockchain case studies; and (3) analyze the strengths, weaknesses, opportunities, and threats (SWOT) of adopting blockchain technology into the construction industry based on findings obtained from thorough analysis of the case studies and surveyed literature. The SWOT analysis is intended to provide guidelines on how to capitalize on the advantages of transactional blockchain in construction projects.

3 Background Information

In 2008, the first blockchain was developed by a mysterious person/group under the alias Satoshi Nakamoto. It became the medium for Bitcoin a year later. In adopting blockchain for bitcoin, Nakamoto introduced several improvements to the technology. He introduced hashing which enabled the timestamp of blocks without requiring them to be signed by a trusted party. He also introduced a difficulty parameter that served to stabilize the rate with which blocks are added to the chain. A blockchain is basically a series of validated units of information named "blocks" connected to one another in a "chain" like manner. It does not have a central administrator or centralized data storage [20]. In other words, a blockchain creates a distributed ledger comprising of records of transactions, the control of which is dispersed among different computers in a network, and this ledger is duplicated to all computers in the network [13]. Therefore, it eliminates the need for centralized entities provided by financial institutions [7].

Blockchain was introduced with cryptocurrencies like bitcoin due to its ability to execute and maintain records of financial transactions in a fast and efficient way. While such capabilities have proven valuable in the finance and banking sector, they have also been the motivation behind expanding blockchain technology into other industries and trades. In the energy sector, blockchain was used to help establish a decentralized peer to peer energy trading model where customers are converted to sellers who are able to sell excess renewable energy to other sellers/customers on the grid [16]. While in the real estate sector, the financial transaction applications of blockchain have introduced several improvements to the means of interaction between buyers and sellers. One application focuses on converting assets into tokens that can be distributed and sold such that the purchased tokens represent ownership of a percentage stake of a property and can be exchanged for a cryptocurrency [10].

There are thousands of blockchains that are publicly offered. A blockchain may incorporate added technologies in its design, such as smart contracts [2]. The practical use of smart contracts surfaced in 2015 with a cryptocurrency called Ethereum. A smart contract is a software coded protocol that self-executes according to the terms of the agreement between the parties. Once a transaction is activated, the smart contract automatically confirms that the contractual obligations related to the transaction have been met, releases the relative payment stored on the blockchain network, then uploads the completed transaction to the ledger, forming a block that is stored on the blockchain network.

Research has shown that blockchain has the potential to facilitate numerous applications in the construction industry such as data recording and tracking, on-site progress monitoring and schduling, and conducting financial transactions on an international level. Nonetheless, actual blockchain implementations in the industry till this day have been limited to mainly procurement management and payment systems. Some implementations focused on monitoring the progress of works on site and processing payments to the contractor accordingly [9]. Other implementations focused on tracking procurement items along the supply chain process as well as conducting financial transactions associated with them [19].

4 Methodology

The authors followed an interrelated multi-step methodology of three steps. Step one includes systematic review of the literature to (1) study the existing applications of blockchain in finance, supply chain, and procurement in the construction industry, (2) investigate documented advantages of utilizing blockchain in financial transactions, and (3) identify documented challenges that face adopting blockchain in financial transactions in the construction industry. Step two entails collection and examination of case studies related to the implementation of blockchain in construction projects. Step three follows to provide detailed content analysis of those case studies. A SWOT analysis was conducted to identify the expected strengths, weaknesses, opportunities, and threats of adopting blockchain technology into the construction industry.

5 Results and Analysis

5.1 *Documented Advantages of Blockchain in Financial Transactions*

The discussed properties of blockchain technology renders it a technological model suitable for implementation in financial transaction applications for the following reasons: (1) optimizes the completion time of financial transactions; (2) promotes the use of smart contracts, which increases the efficiency of financial transactions. Using smart contracts as a transaction protocol for blockchain provides cheaper and faster financial services which enhances the harmony and dynamicity of the system on an international level; (3) increases the transparency of financial transactions thus limiting financial crimes which increases the users trust in the technology and the process [12], and lastly (4) provides information about not only current transactions but also past ones, thus maintaining a record of past transactions easily accessed by users.

While the mentioned above advantages are features that are considered important in construction projects, blockchain has other vital advantages that substantiate its role in enhancing financial transactions specially on the international level. Such advantages include (1) Blockchain cuts fees and tariffs associated with international financial transactions such as foreign exchange transactions, remittances, and credit card transactions. One study estimates that one third of financial transactions fees can be saved by using blockchain [12]; (2) allows the execution of transactions and money transfers without the need for intermediaries; (3) reduces autocratic procedures through digitization and instant verification which otherwise in international financial transactions can be lengthy and troublesome; and (4) facilitate follow-up processes of transactional agreements through automatic verification of records which guarantees these agreements are protected and aid regulatory bodies to keep track of the parties more easily [12].

5.2 *Documented Challenges of Blockchain in Financial Transactions*

When it comes to the use of blockchain in financial applications in the construction industry, several challenges were recognized. (1) Venkatesh and Bala [18] cite implementation challenges as the main reason behind the hesitation of project parties to utilize blockchain in construction projects. In today's world, implementation of new technologies is usually a complex and expensive process, and implementation failures cost millions of dollars. (2) Albayati et al. [2] suggest behavioral challenges to be another reason why blockchain financial applications are not easily adopted in new trades. Lack of behavioral trends such as trust of the technology, previous users experience, and social influence hinders the acceptance of blockchain in new industries such as construction. (3) Nguyen [12] focuses on the legal and regulatory challenges preventing blockchain technology from being easily and widely adopted. A survey conducted on international blockchain users found that willingness to adopt Blockchain-based applications may increase when blockchain applications are regulated and insured by local governments [2]. Until governments dedicate efforts to monitor and regulate transactional blockchain applications, confidence in adopting such technology will remain deficient in the construction industry.

5.3 Motivating Case Studies

A comprehensive literature survey was conducted to collect case studies about the use of transactional blockchain in construction projects. A few case studies were found and are included in this paper for further analysis. To the best of the authors' knowledge, these could be the only documented academic case studies investigating the use of blockchain technology in construction projects.

5.3.1 Case Study # 1

The first case study was as a proof-of-concept example on the applicability of adopting a blockchain framework in an integrated project delivery (IPD) project [6]. It presented a workable procedure for implementing a blockchain network under a IPD project involving various project parties. The developed framework integrated blockchain and smart contracts as a solution to the financial management deficiencies found in IPD projects. The blockchain network included seven parties: client, architect, main contractor, and four sub-contractors (ceiling, lighting fixture, finishing, and doors and windows). There were four main functions through which parties executed all financial transactions: adding participants, reimbursed costs, profit, and cost saving. Financial transactions were defined in terms of the sender, the trade package, the payment milestone, and the value of the transaction. The blockchain consisted mainly of a channel that was used to move data between the project parties on the network. The channel also identified the path of the data when any of the functions of the smart contract was invoked, recorded new data on the network, and which parties were concerned with the added data.

5.3.2 Case Study # 2

The second case study focused on the use of blockchain in the supply chain processes of major construction materials [19]. It presented the utilization of a permissioned blockchain network in the design, selection, and execution of cladding panels in a residential project. The network covered the following procedures within the cladding panels supply chain process: design of the cladding by the architect, product selection from suppliers, specification compliance with Australian authorities, execution adaptability checks by site engineer, client approvals, town council review and approvals, and issuance of final cladding drawings. The network had six main parties: architect, supplier, site engineer, client, building surveyor, and town planner. It had six channels each of which establish private direct communication lines needed between the parties. Only members of a certain channel could see the transactions performed on that channel. Transactions are verified in the channel in accordance with smart contracts installed on it.

5.3.3 Case Study # 3

The third case study investigated the use of blockchain enabled smart contracts in automating the payment processes to subcontractors [4]. It presented the utilization of blockchain in monitoring the progress of supplying and installing façade panels and processing payments to subcontractors. Blockchain, along with BIM and smart contracts, were integrated to automatically detect progress of the work packages and release payments to the subcontractor upon the completion of predefined milestones. The milestones upon which the subcontractor was paid were as follows: completion of panel fabrication, panel in transit, arrival of panel to warehouse, arrival of panel to site, and successful panel installation. Panel location data is captured by sensors then recorded and transferred to the blockchain network and BIM model concurrently. The blockchain double verifies the transmitted information from the BIM model before processing a transaction. For a panel to be considered installed, a contractor representative inspects the panel according to the quality requirements then removes the smart sensor attached to the panel thus signifying its successful installation. Updates of the BIM model can be displayed on smartphones, allowing instant site updates at any location on or off site.

5.3.4 Case Study # 4

The fourth case study also investigated the use blockchain and smart contracts to automate main contractor's payments [9]. The system relies on robotic progress monitoring to automatically translates on-site inspections to payments in accordance with terms of agreement in the smart contract. The smart contract was developed based on the contractual agreement between the Client and Contractor. Addendums to the contract were developed and integrated to the system on a case-by-case basis so that the smart contract was always able to represent the latest agreements between the parties. Cameras and other computer vision-based solutions were utilized to capture progress on site. Progress was presented as activity percent completion and incorporated into a 4D BIM. Based on captured progress data, payments are made to contractor. Captured progress data and corresponding payments were stored and time stamped on the blockchain. Access to data stored on the blockchain was limited to authorized parties, which were determined according to the smart contract. In the case of faulty payments due to poor quality of captured data, poor quality of executed works, or inaccurate analysis of either executed work or data, corrective measures were conducted by the smart contract either by issuing or redacting payments.

5.3.5 Case Study # 5

The fifth case study investigated the use of blockchain in the procurement of major project equipment for an international mega project [19]. It presented the adoption of a public blockchain network with limited members in the procurement of a desalination tower from an overseas international supplier. The blockchain members were: project procurement team and supplier. The blockchain was on Ethereum platform, which was selected due to its turing-complete and programable scripts that support complex modelling and computing. Each of the two stakeholders had a private account on Ethereum, where a smart contract with functions could be executed by those accounts. Financial transactions were carried out using Ether cryptocurrency. The procurement team paid a transaction fee to Ethereum for each transaction made as a services fee to record the transactions into blocks. Transaction 1: a transaction fee was paid by the procurement team to activate the Ethereum network. Transaction 2: The procurement team paid 30% of the contract price in Ether cryptocurrency as a deposit to the supplier. Transaction 3: Upon receiving the advance payment, the supplier delivered the equipment to the agreed upon destination. Transaction 4: The project team received the equipment and inspected the quality. Transaction 5: Once the equipment was approved, the procurement team paid the remaining 70% of the contract price to the supplier and mark the process as complete. All transactions are recorded in blocks and added to the blockchain.

6 SWOT Analysis

A SWOT analysis of the case studies discussed above was conducted to identify the expected strengths, weaknesses, opportunities, and threats of adopting blockchain into the construction industry. Table 1 presents a summery of the SWOT analysis and the remaing of the section presents the detailed findings.

6.1 Strengths

- Works Progress Reporting: Blockchain ecosystems offer robust mechanisms for tracking and reporting on all supply-chain and installation information live across an entire supply chain. Thus, they are able to report on progress of a number of project works and certify those completed to date [4].

Table 1 SWOT analysis for the implementation of blockchain in the construction industry

Strengths	Weaknesses
– Efficient work progress reporting – Prompt contract status reporting – Facilitated BIM integration – Cut costs associated with transaction costs, nonvalue-added tasks, and intermediaries – Assistance in decision making processes – Assistance in project management activities – Ease of information flow – Single source of truth – Facilitated dispute resolution – Enforced transparency and professionalism	– Architecture exclusivity – Paradox of platform choice – Upfront cashflow and associated risks – Lack of applicable clauses in standard forms of contract – Lack of governmental regulations – Scalability – Number of users Data quality and validity

Opportunities	Threats
– Potential improvement in other project management aspects – Less reliance on trust – Easier to use and operate – Less need for manual verification – Potential to eliminate noncompliance and enforces data standards – Better interoperability – Reduce risks and eliminate misalignments – Risks/Rewards sharing – Eliminates geographical barriers – Efficient in automating transactions	– Cryptocurrency volatility – Lack of understanding of parties roles – Flaws in architecture – Smart contracts security – Blockchain inclusivity – Contract Interpretation – Adoption costs – Privacy and confidentiality

- Contract Status Reporting: Among other features, smart contracts have the ability to present the latest amendments/agreements to the contract and status of interim payments. Thus, they can facilitate provision of updated vital information to project parties [9].
- BIM Integration: Data such as progress of project works and activity percent completion can be incorporated into BIMs to enable model driven, integrated communication of progress [9].
- Cost Cutting: Blockchain systems have been shown to cut costs associated with transaction costs and nonvalue-added tasks. transaction costs are the cost of doing business incurred by the parties in conducting any economic exchange such as cost enforces by financial institutions mediating in conducting the transaction. Further, they have proven to lessen the role of intermediaries and accordingly reduce the costs associated with dealing with such intermediaries. Intermediaries are defined as activities or actors that consume time, money, or effort with no added value to the customer [5].
- Assistance in Decision Making Processes: Data and information realized through the use of smart contracts facilitate and have the potential to replace decision making processes of a business organization, and thus reduce management level staff significantly [5].

- Assistance in Project Management Activities: activities and project management tasks automated by the integration of blockchain, smart contracts, and other software add-ins save time and effort of the management team. Such activities include not preparing applications for payments and invoices.
- Ease of Information Flow: All information on the blockchain network is transparent and accessible to the relevant stakeholders and participants. This transparency reduces the possibility of tampering, increases time and cost saving, and promotes traceability [19].
- Single Source of Truth: The distributed ledger of a blockchain warrants the existence of a single source of truth which entails the creation of an application independent, life cyclic, and shared view of the project's information [9].
- Dispute Resolution: The status of the deployed smart contract will only update when the pre-defined requirements are fulfilled at each stage.This helps to eliminate disputes and litigations on payments withheld problems and improve efficiency of contract administration [19]. Further, blockchain technology introduces several protocolsof data communication and access such as FAT protocol where information is securely stored and written to a common data layer accessible by independent application platforms which facilitates dispute resolution procedures [9].
- Transparency and Professionalism: implementation of automated payment systems provided by blockchain networks enforces parties to uphold professionalism, transparency, and reputation by ensuring that parties get paid on-time and in-full [4].

6.2 Weaknesses

- Architecture Exclusivity: Since the architecture of blockchain and smart contracts networks are usually designed by specialized blockchain companies, accessibility and amendments to these ecosystems are exclusively limited to software developers [4]. Tools and templates are required to enable construction industry professionals to engage directly in blockchain technology, for example to write smart contracts [19].
- The Paradox of Choice (choice paralysis): There are currently thousands of blockchains with varying capabilities, performance, and features. Selection of the right platforms is considered a barrier against adoption of blockchain technology in the construction industry [4].
- Upfront Cashflow: Success of most processes adopting blockchain relies on clients providing cash upfront so that funds are available for automated payment release upon completion of the works. This upfront cashflow system may hinder blockchain adoption because it poses a challenge to traditional risk management practices that depend on distributed cash-out patterns throughout project duration [4].

- Contract Drafting: Current payment clauses found in standard forms of contract do not accurately describe the contractual responsibilities of parties intending to contract in a blockchain ecosystem. Contractual modifications need to be made to such clauses to safeguard fulfillment of contractual payments under blockchains and smart contracts [4].
- Governmental Regulations: Like the case in most technological advancements, government regulations cannot keep up with blockchain technology. According to the literature, regulations are expected to take decades to set adequate standards and policies for the adoption of blockchain [5].
- Scalability: Most public blockchains have scalability problems that include transaction processing rate and data transmission latency [5]. Transaction processing rate depends on several factors including performance of the infrastructure, size of the network, block size, and transaction size [19].
- Number of Users: Unlike public blockchain networks where networks have robust number of users with widely distributed grids of nodes, private blockchain networks have far less users, making them more susceptible to bad actors and tampering.
- Data Quality and Validity: Data stored on a blockchain is not naturally trustworthy. Quality of data provided by the blockchain is dependent on the quality of data entered into it. A blockchain cannot assess whether a given input is accurate/true or not. Accordingly, events need to be recorded accurately and comprehensively in the first place so that records in the blockchain can be of value [5].

6.3 Opportunity

- Potential Improvement in Other Project Management Aspects: In addition to its established role in automating progress payments, blockchain in collaboration with smart contract technology has broader impacts on other construction aspects such as law informatics, dispute resolution, and contractual performance. The technology's influence on these aspects still requires further exploration so that optimum benefits are realized in the industry [9]. Future research should consider tracking the scheduling process. For example work packaging within the automated payment system [4].
- Less Reliance on Trust: The autonomus and self-enforcing characteristics of smart contract based blockchains guarantee adherence by stakeholders as well as ensure compliance to guidelines, regulations, and best practices. Thus, they reduce the need for trust between stakeholder working together in a project and reduces the friction between them which encourages new and innovative collaborations in the industry [9].
- Easier to Use and Operate: Some blockchain based applications can be considered easier to use than BIM, because in blockchain once the system is developed and stakeholders consent to the process, it does not require advanced skills to follow the processes and operate the network.

- Less Need for Manual Verification: While Blockchain cannot assess whether a given input is accurate/true as discussed in the weaknesses, secure protocols are added to the system to reduce the need for manual verification of data accuracy once the input data is recorded. Manual verification is proven to impair trust in the construction industry [8].
- Potential to Eliminate Noncompliance and Enforces Data Standards: The smart contract protocols can require compliance with certain data standards and work-flows. They can be coded to exclude the data that does not comply with required exchange standards or is missing certain information from the project records. Instances of noncompliance, whether intentional or by mistake, are detected autonomously and objectively due to blockchain's decentralized consensus algorithm [9].
- Better Interoperability: The transparency in and accessibility to data provided by blockchain systems promotes interoperability based ondata exchange, a significant and costly challenge facing the construction industry at the moment [11].
- Reduce Risks and Eliminate Misalignments: Use of smart contract based blockchain helps mitigate risks and reduce contractual misalignments by enhancing supply chain visibility. An autonomous payment system can enable a direct translation of progress data captured on site to payments, this eliminate intermediate steps that cause the misalignments between parties' interest [9].
- Risks/Rewards Sharing: Sharable recorded information diminishes the barrier of the lack of trust in sharing risks/rewards.
- Eliminates Geographical Barriers: Blockchain enables all participants to have an equal opportunity to track all financial transactions regardless of their geographical location [6].
- Efficient in Automating Transactions: The user-friendliness and practicability of some blockchain implementation tools and its efficiency in automating all transactions would provide a workable solution to existing financial barriers [6].

6.4 Threats

- Cryptocurrency Volatility: Publicly traded cryptocurrencies suffer from price volatility which poses a challenge to construction payments systems and weakens users trust of the system. Nonetheless, increased usage of such cryptocurrencies can stabilize the prices on the long run [9].
- Lack of Understanding of Parties Roles: Blockchain and smart contracts ecosystems offer novel contract administration modes that impacts not only payment systems and cashflows of a project but also the roles of the project's parties. Lack of understanding of this changing dynamic and its consequent effect on the roles and responsibilities of the parties pase major risks to blockchain and smart contract adoption [15].

- Flaws in Architecture: Flaws in the design of some blockchain systems or their implementation can jeopardize the integrity of project data and may cause financial losses [17].
- Smart Contracts Security: Smart contracts security was identified as a primary challenge to the adoption of this technology [17]
- Blockchain Inclusivity: Establishing blockchain systems for all project management activities as well as their variations is believed to be tedious and premature. According to literature, it is recommended to consider blockchains for major or critical activities and that have less variability [19].
- Contract Interpretation: Computerizing the terms of contract can prove challenging or nearly impossible in many cases since a machine-readable code cannot capture all complexities of agreements. Such complexities stem mainly from the need to incorporate human interpretations of contract in smart contracts architecture. Hybrid contracts that encompass both human based interpretation of agreements and autonomous execution of formalized relationships are more feasible and suitable for adoption in the construction industry [9].
- Adoption Costs: Costs of utilizing blockchain may include initial platform building, deployment costs, cloud costs, ongoing maintenance costs, and monitoring costs. These initial costs are considered a barrier against adoption of blockchain technology in the construction industry [19].
- Privacy and Confidentiality: Construction projects utilizing public blockchain networks are subject to have their transactions visible to all users on the platform and accessed without permission. This raises major privacy and confidentiality concerns for project stakeholders [19].

7 Conclusion and Future Work

This paper has presented a systematic literature review and content analysis on the implementation of blockchain technology in the construction industry. The analysis of the case studies showed that all blockchain systems that were adopted in construction projects were integrated with smart contracts. These blockchain-smart contract ecosystems were mainly utilized to optimize two construction management processes: procurement management and payment systems. The applications of such systems included supply chain monitoring, on-site progress monitoring, cutting financial and/or managerial intermediaries, financial transactions between two or more parties.

Future research could focus on exploring new applications of blockchain in the construction industry. For example, it was seen that most of the case studies included in the review have stopped short of utilizing blockchain all the way through till monetary exchange. The use of cryptocurrency is still considered a barrier against adoption of blockchain technology in the construction industry and thus needs further investigation. Additionally, currently used applications can also be explored for further enhancements. For example, currently used smart contract are considered not fully smart because they fail to capture and process some construction contractual procedures. Smart contracts development can be further explored to consider two main aspects: (1) comprehensive definitions of tasks required to complete construction project activities, and (2) inclusive listings of all possible variants related to a given task such that smart contracts are able to take into account all potential scenarios. More research and coding efforts can be spent to achieve increasingly "smart" contracts.

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Improving the Reliability of Electric Power Infrastructure Using Distributed Solar Generation: An Agent-Based Modeling Approach

G. G. Ali and I. H. El-adaway

1 Introduction

Natural disasters are a major cause of the disruption of electric power services. An estimated 679 widespread weather-related power outages occurred in the US between 2003 and 2012, each affecting at least 50,000 customers. It is also estimated that those weather-related outages, in combination with the aging infrastructure in the US, cost the economy an inflation-adjusted average of $18 to $33 billion [5, 19]. As such, the need to increase the resilience of the electric power grid and systems against severe weather-related events. One of the developing solutions to overcome that challenge is to integrate distributed energy resources in the grid to improve resilience [4, 21, 44].

Distributed Solar Generation (DSG), which are most typically Photo-Voltaic (PV) cells, is popular as a small-scale source of electric power. They are easy to install, environmentally friendly, and may offer cost savings compared to consuming power to the conventional grid. The EIA [11] defines a small-scale solar generation as having a capacity of less than 1 Megawatts, and typically they have a 5-Kilowatt capacity. Small-scale solar represents 33% of the total solar generation in the US, including PV and thermal. The number of PV installations is increasingly growing. The trend has been significant in some locations, such as California, which accounts for 40% of distributed PV capacity, while the following nine states account for 44%. This trend has been attributed to a combination of high electricity prices, abundant solar resources, and incentives that promote the installation of DSG.

The shift from centralized generation to smaller distributed generation is expected to improve the level of electrical power infrastructure reliability and effectiveness [10, 13]. By design, DSG can be operated to complement the power from the conventional grid or can be operated in complete isolation from the grid in an "*island mode*". Thus,

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they can be an effective method to reduce the consequences of natural disasters in case of emergency, in addition to their many other benefits. Many researchers in have investigated the benefits of distributed resources and microgrids in improving the reliability of the power infrastructure, both pre-and-post- disaster [1, 29, 42, 45]. Nosratabadi et al. [30] present a comprehensive literature review on the subject. However, there is a lack of research that investigates the benefits of promoting DSG on the resilience of electric power infrastructure as a complex system and from a multi-disciplinary perspective.

2 Goal and Objectives

The goal of this research is to investigate the benefits of the adoption of DSG in improving the reliability of power infrastructure systems against natural disasters. As such, a framework for the complex System-of-Systems (SoS) simulation of the power infrastructure and wholesale power markets was developed The proposed simulation framework combines Agent-Based Modeling (ABM) with scenario-based resilience analysis of the power infrastructure to study the benefits of DSG. Accordingly, the simulation framework was tested using a hypothetical case study that combines real and synthetic data to verify the robustness of the framework. Ultimately, this research contributes to the body of knowledge by highlighting the benefits of promoting and incentivizing DSG in high-risk areas that are susceptible to natural disasters.

3 Background

3.1 Distributed Generation

DSG, and distributed generation in general, are a promising solution to increase sustainability, reduce costs, and improve system resilience [36]. Accordingly, it has the subject of many research endeavors and promising innovations. From the electrical engineering perspective, researchers and practitioners are attempting to improve the integration of distributed resources into the electric grid and solve the associated technical obstacles and uncertainties [26, 30, 34]. Other research areas have been focused on the economic and financial aspects that influence and motivate the installation of distributed generation [8, 46]. Distributed generation and micro-grids have also been researched as a method to improve resilience [1, 4]. Examples include, among others: using dispatchable power sources [44], smart storage of electricity from PV cells at the household level [21], among other. However, there are many questions, obstacles, and uncertainties associated with integrating distributed generation into the power infrastructure generally and specifically to improve system resilience.

3.2 Complex System Simulation Using Agent-Based Modeling (ABM)

ABM is a technique that enables the simulation of complex SoS in a bottom-up approach. It relies on the simulation of simple separate agents that have simple rules and can interact in a complex environment. This enables the analysis of the emergent behavior of the higher-level SoS. ABM has been effectively used in many applications, such as infrastructure systems [7], occupant energy consumption in buildings [2, 6], construction safety [9], bidding strategies [3, 18], and disaster management [14, 15], among many other applications.

The ABM method has also been effectively used to simulate the complex behavior of electrical power markets [16, 17, 38, 39]. Wholesale electric power markets involve a complex behavior emerging from several stakeholders including utilities, generators, consumers. The system is affected by electrical engineering parameters that involve transmission line constraints and generation parameters, combined with economic rules of supply and demand. As such, this research relies on ABM to capture the holistic behavior of the electrical power infrastructure and market, combined with the resilience of the electric grid granted by DSG.

4 Methodology

The methodology of this research involves multiple steps, as shown in Fig. 1, and include: (1) Development of the ABM model including parameters for the economics of supply and demand; (2) Implementation of a module for system resilience analysis and allocation of DSG resources. Finally, (3) the model is tested against a hypothetical case study of an electric power grid that combines synthetic and real data to verify the behavior of the model. The following sections describe each part of the model.

4.1 ABM Development

The developed framework relies on ABM to grasp the complexity of the interaction between the stakeholders and elements in electrical power infrastructure and wholesale power markets. Accordingly, the agents in the ABM model include the following: (1) Nodes: which represent locations in the electrical power grid such as

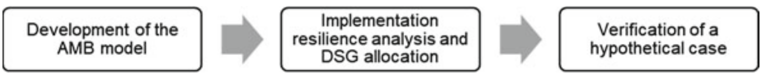


Fig. 1 Outline of the methodology

cities or towns; (2) Load Servicing Entities (LSEs): which represent utilities, located at nodes, buy power from generators, sell power to their customers; (3) Generators: which are located at nodes and sell power to the LSEs; and finally, (4) Transmission lines; which connect the nodes and transfer power between them.

To calculate demand and generation for the LSEs and generators, the model relies on a combination of two methods: (1) DC Optimal Power Flow (DC-OPF) and (2) the rules of the economics of supply and demand. This method was proven effective in previous literature to study the dynamics of wholesale power markets [38, 39]. DC-OPF is a viable choice for this framework because it has the required combination of complexity and performance. The supply part of the model is defined by the supply parameters of the generators, a_g and b_g, for each generator g, as shown in Eq. 1. The generators also have additional fixed costs and maximum generation capacity. These parameters depend on the type of generator such as coal, nuclear, or natural gas plants. For the demand part, each LSE j, has demand parameters, c_j and d_j, as shown in Eq. 2. Also, each LSE has demand constraints. Finally, the equations are grouped into the DC-OPF with the objective function shown in Eq. 3. The objective function includes phase angles δ and a penalty π, which mainly defines the transmission between the nodes, which is affected by the reactance of the transmission lines. The model also includes the required parameters associated with node balance, demand constraints, generation constraints, and transmission constraints.

$$GenerationCost_g = a_g \cdot P_g + b_g \cdot P_g^2 \tag{1}$$

$$DemandSurplus_j = c_j \cdot P_j - d_j \cdot P_j^2 \tag{2}$$

$$Minimize: \left(\sum GenerationCost_g - \sum DemandSurplus_j\right) + \pi \sum_{km} [\delta_k - \delta_m] \tag{3}$$

Ultimately, the model calculates the commitment of each generator, and the demand of each LSE, among other useful outputs, using a Dual Stage Optimization problem [20]. By combining ABM, DC-OPF, and the economics of supply and demand, the model can define the dynamic behavior of the power infrastructure and market as a complex SoS. This allows it to be used as a testbed to add the functionality to perform resilience assessment.

The parameters for the supply in the model are the parameters defining the generators, and they are constant during the simulation. However, the demand parameters change according to the number of customers connected to the grid, i.e. not using DSG. To account for the shifting demand parameters, the demand parameters c and d are calculated using regression analysis of data that is made publicly available online by the US Energy Information Administration [12]. The data covers monthly electricity demand, prices, and the number of customers. After cleaning the data, it includes 7,497 records. The data is used to fit Eq. 4 using panel regression and find parameters α_1 and α_2. The regression achieved $R^2 = 0.890$ and

$AdjustedR^2 = 0.889$, and the $p - values$ were below 0.005, which marks an acceptable fit. During the simulation, parameters α_1 and α_2 are calculated and easily substituted to find parameters c and d in the demand equations of the simulation. The data from the EIA is also used to calculate the minimum and maximum power demands to be within an acceptable percentile of the data. Since the data represents average monthly demands, a factor of 1.2 is used to convert it to a peak hourly demand at around 5 pm.

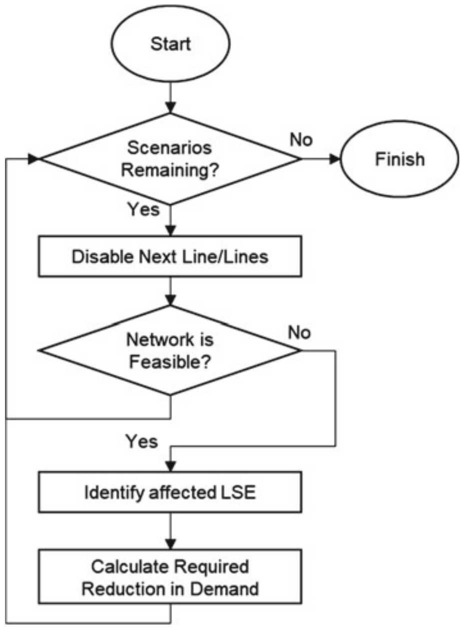
$$Price\left(\frac{\$}{MWh}\right) = \alpha_1 \times \frac{HourlySales\left(\frac{MWh}{Hour}\right)}{Log(NumberofCustomers)} + \alpha_2 \times StateDummy + Contant + \epsilon \quad (4)$$

4.2 Resilience Analysis and Allocation of DSG

With the ABM developed to perform complex simulations of the dynamics of the electrical power market, higher-level functions are added to perform resilience analysis using scenario-based analysis. The module assumes that when a transmission line is disabled, the electrical grid may have become in one of two states: (1) the power flow can shift in response without disruption to power service availability, or (2) the network becomes unstable, one or more of the LSEs cannot be supplied with the required demand, and operators have to force engineered blackouts to avoid cascading damage to the system. Therefore, The goal of this module is to determine the amount and location of DSG required to maintain power service availability if a line is disabled during natural disasters. To achieve that, the algorithm shown in Fig. 2 is followed.

The general outline of the module goes through the following steps: (1) For each scenario, one transmission line in the simulation is disabled and the model attempts to calculate the OPF; (2) If the network is feasible, then the line is not critical to the operation of the grid; (3) If the problem is not feasible, then the disabled line is critical to the operation of the simulation and the demand needs to be calibrated to regain stability. To calibrate the model in case a line is identified as a critical line, the model identifies the LSE that is susceptible to a shortage of demand, and determines the maximum demand that can be connected to the grid. The remaining demand has to be disconnected. By increasing the adoption of DSG at the identified LSEs to the minimums calculated, future disruptions caused by natural disasters may be mitigated.

Fig. 2 Overview of resilience algorithm



4.3 Hypothetical Case Study

To test and verify the behavior of the model, a hypothetical case study is used. The case combines real data that is available from sources such as the EIA [12] combined with synthetic data created with reasonable assumptions and approximations to real counterparts. Complete information of grid details is not easily available due to many obstacles such as limitation of information, complexity, and security. The objective of the presented case study is to test and verify that the model can achieve the required functionalities and that it can be used in similar applications using other cases.

A representation of the case study is shown in Fig. 3. It includes six nodes, five generators, six LSEs, and seven transmission lines. The parameters of the LSEs, generators, and transmission lines are shown in Tables 1, 2, and 3, respectively. Table 1 shows the number of customers for each LSE. It should be noted that the number of customers is dynamic, meaning that if the model finds that an LSE is affected by a scenario, it will lower the number of customers in that LSE to limit the maximum demand and regain service availability. Also, the LSEs have demand parameters, as discussed previously, which are calculated during the execution of the simulation and are affected by the number of customers. Table 2 shows the parameters of the generators, which includes the supply parameters a and b, and the maximum generation capacity. During the simulation, the commitment, i.e. the actual generation, of each generator is calculated. Finally, the transmission line parameters are shown in Table 3. Those include the reactance, which affects the phase angles between the nodes, and the maximum capacity of each line. Both parameters affect

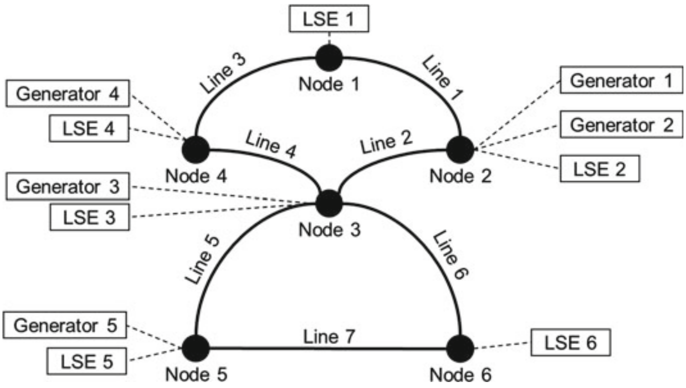


Fig. 3 Representation of the electrical power grid for the hypothetical case study

Table 1 LSE parameters

LSE	Number of customers
1	150,000
2	330,000
3	175,000
4	155,000
5	140,000
6	175,000

Table 2 Generator parameters

Generator	a	b	Max capacity (MW)
1	18.00	0.00012	700
2	56.50	0.00800	450
3	18.28	0.00012	2000
4	18.10	0.00012	240
5	10.00	0.00200	1200

Table 3 Line parameters

Line	Reactance (Ω)	Capacity (MW)
1	40	100
2	60	100
3	100	80
4	55	100
5	65	70
6	85	100
7	55	75

the flow of power in the grid between the nodes. Overall, the configuration of the grid is set so that it demonstrates the dynamic response of the grid when a line is disabled. For example, if line 1 is disabled, then node 1 will receive power through line 3 only, instead of being connected through lines 1 and 3 simultaneously. Also, the configuration of the grid is set so that each node is connected by at least two lines, so that none of the nodes are left unconnected if a singular line connected a node to the grid and was disconnected in a scenario.

4.4 Tools and Software Used

The model was developed entirely using the programming language Python, which is a very suitable environment for scientific and engineering applications, with an advantage for development speed [28, 32]. Several open-source packages are used, including; Numpy for numerical computation [31, 40], Matplotlib [23], and Seaborn [43] for plotting, Pandas for data structures [27], and Statsmodels [35] and Linear-models [37] for statistical analysis, SciPy [41] for scientific computing and curve fitting, Networkx [22] for network analysis and plotting, Scikit-learn/Sklearn [33] for machine learning, and Numba [25] as a JIT compiler. Development relied on free and open-source development environments such as Microsoft's Visual Studio Code and Jupyter Notebooks [24].

5 Results and Analysis

The results of the hypothetical case study concerning maximum capacity for each LSE, demand at each LSE, and generator commitments are shown in Tables 4, 5 and 6, respectively. As shown in Table 4, the results show that scenarios 2, 4, and 5, did not affect the stability of the grid. However, scenarios 1, 3, 6, and 7, affected

Table 4 Maximum capacity of customers connected to the grid

Scenario	Line tested	LSE 1 (%)	LSE 2 (%)	LSE 3 (%)	LSE 4 (%)	LSE 5 (%)	LSE 6 (%)
1	Line 1	69	100	100	100	100	100
2*	Line 2	100	100	100	100	100	100
3	Line 3	86	100	100	100	100	100
4*	Line 4	100	100	100	100	100	100
5*	Line 5	100	100	100	100	100	100
6	Line 6	100	100	100	100	100	55
7	Line 7	100	100	100	100	100	74

*Scenario had no effect

Table 5 Total demand at Each LSE

Scenario	Line tested	LSE 1	LSE 2	LSE 3	LSE 4	LSE 5	LSE 6
0	None	140.97	636.64	337.61	299.03	270.09	175.00
1	Line 1	79.87	636.64	337.61	260.13	270.09	175.00
2	Line 2	140.97	636.64	337.61	299.03	270.09	175.00
3	Line 3	100.00	636.64	337.61	299.03	270.09	175.00
4	Line 4	115.75	636.64	337.61	224.25	270.09	175.00
5	Line 5	140.97	636.64	337.61	299.03	270.09	175.00
6	Line 6	140.97	636.64	337.61	299.03	270.09	75.00
7	Line 7	140.97	636.64	337.61	299.03	270.09	100.00

Table 6 Total generation by each generator

Scenario	Line tested	Generator 1	Generator 2	Generator 3	Generator 4	Generator 5
0	None	643.36	0	698.21	240.00	277.78
1	Line 1	644.11	0	597.45	240.00	277.78
2	Line 2	700.00	36.64	604.92	240.00	277.78
3	Line 3	700.00	0	600.59	240.00	277.78
4	Line 4	700.00	0	541.56	240.00	277.78
5	Line 5	643.36	0	630.90	240.00	345.09
6	Line 6	643.36	0	460.90	240.00	415.09
7	Line 7	643.36	0	560.90	240.00	340.09

the grid, and the demands needed to be reduced to maintain stability. By referring again to the configuration of the grid, in Fig. 3, it is logical that scenarios 1 and 3, which disconnect lines 1 and 3, would affect LSE 1, which limited maximum demand at 69% and 86% respectively. Similarly, LSE 6 was affected in scenarios 6 and 7, where the maximum demand needed to be reduced to 55% and 74% respectively. This shows that the rest of the demand needs to be supplied by other backup sources, and the adoption of DSG to those minimum requirements would mitigate future disruptions. Also, Table 5 shows interesting results for the demands at the LSEs. For example, the demand at LSE 4 changes through the scenarios although it was not directly affected by the interruption induced to transmission lines. Similarly, the generators were affected, as shown in Table 6. For example, in scenario 2, Generator 2 became operational, and Generator 1 had increased commitment compared to the base Scenario 0, to fill the demand left by the reduced commitment of Generator 3. This shows the complex dynamic of the power infrastructure and market where power is generated to fill demand at the lowest locational prices. Also, it shows that relieving the demand using DSG, combined with the dynamics of the wholesale power market, can increase resilience against natural disasters.

6 Conclusion and Future Work

Natural disasters cause major disruptions to the electrical power infrastructure. DSG can mitigate the effect of those disruptions by providing an alternative and distributed source of power located at the consumers. Accordingly, the goal of this research is to investigate the benefits of the adoption of DSG in improving the reliability of power infrastructure systems against natural disasters. This research presents a framework that simulates the complex SoS that involves the agents in the power infrastructure market using ABM, combined with resilience analysis considering the disruption of services caused by natural disasters. The model was tested and verified using a hypothetical case study that combines real and synthetic data. The results show the robustness of the model in determining the location and amount of DSG needed to mitigate the effects of natural disasters. Also, the results show the dynamics of the power infrastructure and market, combined with DSG, in shifting generation and transmission in response to disruptions of service. Ultimately, this research contributes to the body of knowledge by highlighting the benefits of promoting and incentivizing DSG in high-risk areas that are susceptible to natural disasters. Future work is expected to include more diverse scenarios of failure determined by the types of natural disasters. Also, as this research focused on the failure of transmission lines, future work may consider the effects on other types of stockholders, such as generators or households. Finally, future work can take different approaches, techniques, or objectives to optimize the location of DSG considering the total operational cost of the network.

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Integrating Simulation and Emission Models for Equipment Cost Analysis in Earthmoving Operations

Nicolas Diaz and Ming Lu

1 Introduction

Modern construction industry is one of the largest employers and leading industries of the Canadian economy. However, it is also among the largest consumers of natural resources and perceived as a business that faces significant management obstacles. One of these obstacles lies in the management of heavy equipment in civil and infrastructure construction.

A fleet of heavy equipment is an essential part of the site materials handling system and vital to the successful business operations of a heavy construction contractor. Fleets management is a significant undertaking on construction projects as it has tremendous implications in achieving completion of projects under schedule and budget constraints. Additionally, operation and maintenance costs of construction equipment make up a considerable amount of the total project cost. Moreover, the extensive use of heavy equipment partly accounts for the fact that the construction sector is a substantial producer of pollutants.

Due to the growing emphasis that public and private organizations place on the implementation of sustainable practices, construction managers are compelled to consider non-financial criteria in making decisions on purchasing, operating, and maintaining, and replacing equipment. Unfortunately, there are limited studies that provide fleet managers with guidance in regards to achieving sustainable goals on construction projects.

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In order to improve the sustainable performance of construction projects, it is necessary to evaluate the greenhouse gas emissions of construction equipment as a cost factor. Despite numerous prior studies attempting to measure greenhouse gas emissions during construction operations, a methodology that links such measurements to operations simulation models has yet to be established. Therefore, an application framework that links emission measurements to the simulation of construction activities is desired.

In order to assist members of the construction industry in accomplishing sustainable goals, this study proposes an application framework based on the application of environmental assessment and the use of simulation models. The framework facilitates fleet managers to maximize the cost-effectiveness of equipment while reducing their environmental impacts. The application framework is based on general concepts of lean and green construction and published data and analyses of field measurements for estimating fuel use and emission rates of construction equipment [8].

2 Literature Review

2.1 Simulation Models

Construction engineering assembles physical components and involves professionals from the beginning to the completion of a project life cycle. Bokor et al. [4] mentioned, "Construction simulation is a useful technique that replicates reality and provides valuable information on construction works (p. 1859)". The use of simulation tools in the construction industry focuses on techniques and procedures that address numerous challenges during the construction period in a dynamic, fast-changing environment.

The use of simulation models leads to implementing new approaches in the construction management process in order to solve problems related to the planning and execution of works, such as imprecise scheduling and inadequate allocation of roles and resources [7]. Simulation software provides a dynamic environment for analyzing computer models while solving real-world problems in a safe and efficient fashion. There are diverse simulation software systems that are available for academic and commercial purposes based on discrete event simulation. For instance, SIMPHONY, as a simulation software, offers unique capabilities. As AbouRizk et al. [1] mentioned, "Simphony was developed to allow simulation tools to build on the fly… also allow the development of systems, called templates, which use icons that closely represent elements from real-world problems to build simulations models (p. 24)".

Simulation is a powerful decision-support tool for decision makers to observe the effect of projects' conditions upon performances. Moreover, simulation tools provide greater flexibility towards functionalities such as generating random numbers from probability distribution functions, advancing simulation time, determining the next event, collecting and analyzing data, reporting the results and adding or deleting records. These characteristics are instrumental in developing a better alternative by reducing risks, budget development, claims, dispute resolution, planning and control.

2.2 Equipment Fuel Use and Emission Rate Estimates

A major limitation the construction industry aims to overcome is the assessment of environmental impacts resulting from executing projects. One aspect of this limitation is the ability to determine how much environmental damage the machinery selected by construction managers actually causes during the construction processes. Early studies attempted to quantify the environmental impact of equipment. For example, Ahn et al. [2] provided a point of reference to analyze the energy consumption and air emissions resulting from buildings and construction sectors in the U.S and Canada and demonstrate the effort to achieve environmentally sustainable construction processes. On the other hand, Abolhasani et al. [3] in *Real World in use Activity, Fuel Use, and Emissions for Nonroad Construction Vehicles: A Case Study for Excavators,* stressed the relevance of "accounting for intercycle variability in real-world in-use emissions to develop more accurate emission inventories. (p. 1033)" The author pointed out a vital need to study real-world, on-board data to understand the relationship between construction equipment duty cycles concerning energy use and emissions. Most of these early studies developed methods that quantified emissions and fuel use based on steady-state engines. As such, these methods did not consider in-use equipment activities, thus producing results that might not accurately reflect the actual amount of pollution created in the field.

Lewis [8] realized the need to determine fuel use and emission rates of equipment based on in-use measurement methods, who decided to quantify the actual construction activity and its influence on fuel use and emissions via field data collection. Nevertheless, constantly measuring fuel use and emission of pollutants was expensive and impractical. Thus, devising a data-driven method for equipment field emission performance estimating that could be used in the same manner as other standard construction estimates was made the ultimate goal. Findings from [8] were thoroughly reviewed in the present research.

2.2.1 Field Measurements

The initial obstacle to conducting an appropriate field measurement is an adequate characterization of vehicle emissions. Given diesel vehicles, the primary pollutants are NOx, HC, CO, and PM. Factors that influence the amounts of these pollutants generated include engine activity and task durations.

In his data collection, Lewis [8] applied a method that consisted of second-by-second engine activity and emission measurements through a portable emissions monitoring system (PEMS). A PEMS was a small and light device mounted on

Table 1 Summary of equipment types

Equipment type	Equipment tested
Backhoe	8
Bulldozer	6
Excavator	3
Motor grader	6
Off-road truck	3
Track loader	3
Wheel loader	5

motor equipment and connected to an engine to gather air pollutant emission data. To create the connection between PEMS and an engine, sensors and a sample probe were inserted into the tailpipe while the vehicle performed work. As the probe collected information on pollutants, the sensors monitored the engine performance by tracking Revolutions Per Minute (RPM), values for Manifold Absolute Pressure (MAP), and Intake Air Temperature (IAT) [8].

Lewis [8] also used PEMS to measure specific vehicle activities and engine parameters. These vehicle activities are known as 'activity modes' including idling, moving, loading, compacting, and more. The duration of each activity mode was measured by seconds, while specific engine parameters were monitored (RPM, IAT, and MAP). Thus, the information from these activity modes and engine parameters was combined to establish a relationship that characterized special diesel equipment emissions.

For his study, Lewis [8] selected construction equipment that produced the highest quantities of pollutants based on analyses using the EPA NONROAD model [6]. A summary of equipment types and quantities is given in Table 1.

Once the data was collected, the following steps were taken to estimate fuel use and emission rates of construction equipment [8]:

1. Identify and quantify equipment attributes that affect fuel use and emission rates.
2. Perform an engine modal analysis for each type of equipment.
3. Develop engine modal fuel use and emission rates for each engine mode though statistical analysis.
4. Determine time spent in each engine mode and fraction of fuel used in each engine mode through the study of representative duty cycles.
5. Establish the weighted-average fuel use rate cycle by multiplying the modal fuel use rate by the fraction of time spent in each engine mode.
6. Establish the weighted average emission rate for each pollutant by multiplying the modal emission rate for each engine mode by the fraction of fuel used in each engine mode.
7. Convert the mass per fuel used weighted-average emission rate to a mass per time weather average emission rate.

2.2.2 Modal Analysis

Two modal analyses were conducted to determine the impact of equipment and engine activity on fuel use and emission rate, namely, *activity modal analysis* and *engine modal analysis* [8].

The activity modal analysis categorized data based on the working state of equipment, such as idling or working. This categorization was performed by the PEMS and the laptop that recorded second-by-second data by activity mode categories; then the average fuel use and emission rates were calculated for each activity mode. Next, the measuring devices would express the average use rate on a mass per time basis, i.e. grams of fuel consumed per second (g/s).

By categorizing second-by-second data into activity mode categories and then calculating average fuel use and emission rates for each activity mode, the average fuel use rate was expressed in terms of grams of fuel consumed per second (g/s). The rate of emissions was expressed on a mass per time basis (g/s) or a mass per fuel basis (g/gal). Hence, emission rates were sensitive to idling and non-idling modes with respect to fuel consumption. However, time-based emission rates were more sensitive to engine loads imposed by working modes than fuel-based emissions rates [8].

The engine modal analysis categorized data based on a range of loads imposed on the engine. The values of MAP were normalized to use as an indicator of engine performance. The normalized values of MAP ranged from 0 to 1, creating ten engine modes. These modes were defined as 0.0–0.1, 0.1–0.2, 0.2–0.3, 0.3–0.4, 0.4–0.5, 0.5–0.6, 0.6–0.7, 0.7–0.8, 0.8–0.9, and 0.9–1.0. For example, engine mode 1 refers to normalized values between 0.0 and 0.1.

Through the engine modal analysis, fuel use and emission rates were quantified by arranging second-by-second data into engine mode categories, resulting in average fuel use and emission rates for each. The engine modal analysis produced the fuel use rates in terms of grams of fuel consumed per second (g/s).

By calculating the average fuel use and emission rates for each engine mode, the average fuel use rate was established in terms of grams of fuel consumed per second (g/s). This is because emission rates were highly sensitive to each engine mode and fuel-based emission rates are more robust for equipment emission estimating purposes [8]. It is noteworthy though the conventional unit to measure emission uses a mass unit (ton), the rate of emissions is expressed as a mass per time basis (g/s) or a mass per fuel in terms of grams per gallon of fuel used (g/gal).

2.2.3 Fuel Use and Emission Rates Through Modal Analysis

The fuel and emission rate of each pollutant for each engine mode was determined by using the average fuel use and emission rate for each mode or by developing a mathematical relation for each engine model based on multiple linear regressions (MLR).

Table 2 Fuel use rate models for each engine mode [8]

Mode	Model	S	R:	R^2-adj
1	Fuel [g/s] = 0.6 1	NA	NA	NA
2	Fuel [g/s] = − 0.364 + 0.0112 HP + 0.565 TIER_0	0.5	76	75
3	Fuel [g/s] = − 0.620 + 0.0166 HP + 0.876 TIER_0	0.7	77	75
4	Fuel [g/s] = − 0.882 + 0.0216 HP + 1.29 TIER_0	0.9	76	74
5	Fuel [g/s] = − 0.908 + 0.0244 HP + 1.56 TIER_0	1.0	77	76
6	Fuel [g/s] = − 1.05 + 0.0283 HP + 1.81 TIER_0	1.1	77	76
7	Fuel [g/s] = − 1.30 + 0.0332 HP + 2.03 TIER_0	1.3	78	76
8	Fuel [g/s] = − 1.39 + 0.0368 HP + 2.47 TIER_0	1.4	78	77
9	Fuel [g/s] = − 1.68 + 0.0422 HP + 2.93 TIER_0	1.6	80	78
10	Fuel [g/s] = − 1.66 + 0.0458 HP + 2.93 TIER_0	1.6	81	80

The development of mathematical equations to relate special equipment attributes with its fuel use and emission rates was based on the data collected from 34 construction vehicles and the MLR technique. These attributes included horsepower, displacement, model year, equipment type, and engine tier. The predictive models were developed for engine modes 1–10, and similarly to the average fuel use and emission rates, some models included data with outliers and other excluded outliers. For emission rate estimates, Lewis developed models for the emission rates of NO_x, HC, CO and PM given engine mode 1–10. Table 2 shows the developed relationships for estimating the fuel use rate for each engine mode.

The fuel use rate models for each engine mode (shown in Table 2), and the average emission rate per engine mode provided the basis to determine the weighted average fuel use rate (gal/h) and the weighted average emission rate (g/h) by [8].

3 Proposed Framework

It is critical to evaluate greenhouse emissions as a cost factor in construction planning, equipment selection and cost estimating in consideration of the urgency for preventing further environmental decay. Hence, the objective of the proposed framework, shown in Fig. 1, is to assist construction managers to select the most sustainable fleet available. A sustainable fleet represents an equipment combination that reduces the time spent in non-productive activities (such as idling and waiting), minimizes the production of emissions while also delivering a high production rate.

As seen in Fig. 1, the framework is divided into two components: Lean Operation and Green Operation. The Lean Operation component is used to select equipment and plan work by implementing lean construction concepts, such as reducing idle time and eliminating unnecessary tasks. The resulting fleet configuration based on this component produces a higher operation efficiency rate and a better assets

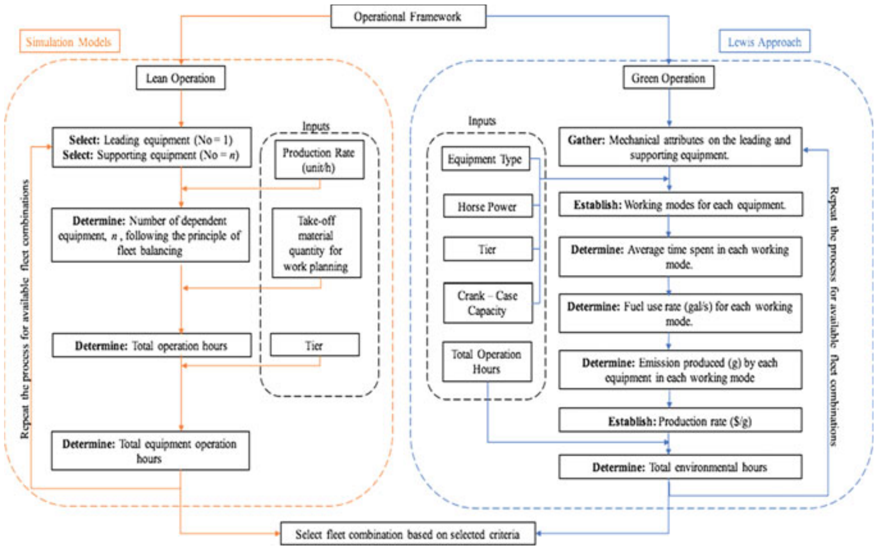

Fig. 1 Applicable framework for equipment costs analysis and environmental assessment

utilization rate but does not necessarily provide a fleet configuration that attains high performance in connection with greenness and sustainability.

The Lean Operation component aligns with the basic principle for fleet balancing. Fleet balancing aims to realize the full capabilities of a particular piece of equipment by allowing it to set its productivity as high as possible. This equipment governs the construction system and is referred to as the *leading resource*. The other pieces of equipment that make up the construction system are set to match the leading equipment's production rate. In most instances, marginal overcapacity on the production rate of supporting equipment is allowed to ensure that the leading resource does not experience idling or waiting time, thus allowing it to operate at its full production capacity. Overall, the use of the Lean Operation component in the proposed framework improves a construction system's operation efficiency by maximizing equipment utilization efficiencies.

On the other hand, the Green Operation component enables the framework to consider greenhouse gas emissions as a type of waste, a financial item and a performance indicator. Consequently, the Green Operation component uses quantification methods to estimate the fuel use rate of construction equipment and determine the amount of pollutants emitted. The framework bases its Green Operation component on the quantification methods proposed in [8].

In order to use the framework, the following steps should be followed:

1. Select leading equipment and supporting equipment: from all the equipment involved in the construction operation, the leading equipment governs the construction system by setting the system's production rate. Simultaneously, the

supporting equipment assists in completing the tasks by matching the system's production rate.

2. Set the production rate of the construction system: the system's production rate can be determined through the application of DES programs such as SIMPHONY. It is critical for this DES modeling platform to accurately represent the process of operations in terms of interaction between equipment involved and cycle times to complete tasks.
3. Takeoff material quantity for work planning: This step can also be accomplished with design models or by taking field measurements.
4. Determine total operation hours: The total operation hours can be obtained through the use of simulation models.
5. Apply Lewis' methodology to estimate fuel use (gal/h) and emission rates (g/h):
   - 5.1 Identify and quantify equipment attributes that affect fuel use and emission rates (Equipment type, engine size, engine age, engine load, and engine tier).
   - 5.2 Perform an engine modal analysis for each type of equipment.
   - 5.3 Develop engine modal fuel use and emission rates for each engine mode through evaluation of field measurements data.
   - 5.4 Determine time spent in each engine mode and fraction of fuel used in each engine mode through the study of representative duty cycles.
   - 5.5 Establish the weighted-average fuel use rate by multiplying the modal fuel use rate by the fraction of time spent in each engine mode.
   - 5.6 Establish the weighted average emission rate for each pollutant by multiplying the modal emission rate for each engine mode by the fraction of fuel used in each engine mode.
   - 5.7 Convert the mass per fuel use weighted-average emission rate to a mass per time weighted-average emission rate.
6. Establish an hourly rate for equipment operation and an emission fee: The hourly rate of equipment operation depends on the type of equipment being used and the rate for the operator. For emissions, a fee for the production of emission ($/g) needs to be established, so the vehicle's emission rates can be used as a cost indicator. The quantification of the fuel use rate (gal/h) and emissions rate (g/h) are obtained through Step 5.
7. Determine the total operational and environmental cost.
8. Evaluate different fleet combinations by repeating the steps (1–7).
9. Select fleet combination: Once all the fleet combinations have been analyzed, it is possible to select the fleet combination based on specified criteria, whether it is the most environmentally friendly combination, or the fleet associated with the lowest operational cost, or a trade-off between the two objectives.

4 Application Case

This section introduces a case study used to demonstrate the applicability of the proposed framework in evaluating construction processes in consideration of environmental cost factors.

4.1 Problem Statement

An industrial site undergoes development and requires rough grading operations. Currently, the proposed campground area is approximately 2000 m long and 650 m wide and has 584,308 bank cubic meters (BCM) of soil that needs to be handled. The general arrangement for the site is shown in Fig. 2. The site is designed to have two drainage ponds.

The site is reconstructed into a grid model, as shown in Fig. 3, to display the localized areas that require either filing or cutting volumes of earthwork. There are 48 grids sized at 150 m by 150 m, and each grid has an earth volume specified in BCM. Cut volumes are denoted with " − " while fill volumes are denoted in " + ".

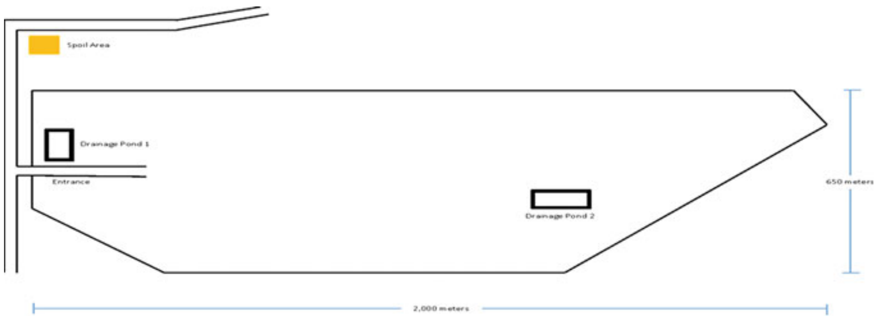

Fig. 2 Site layout

Cell 1 -15000	Cell 2 -3700	Cell 3 +3700	Cell 4 +9000	Cell 5 +9000	Cell 6 +8000	Cell 7 -1000	Cell 8 -11200	Cell 9 -2300	Cell 10 -22000	Cell 11 -6900	Cell 12 +11200
Cell 13 -62600	Cell 14 +22500	Cell 15 +23800	Cell 16 +26000	Cell 17 +23000	Cell 18 +22200	Cell 19 +8100	Cell 20 -24800	Cell 21 -9900	Cell 22 -2200	Cell 23 +14300	Cell 24 +7900
Cell 25 -3700	Cell 26 +22500	Cell 27 +28100	Cell 28 +23000	Cell 29 +24300	Cell 30 +14200	Cell 31 -12400	Cell 32 -34400	Cell 33 -72500	Cell 34 -28500	Cell 35 -2500	Cell 36 0
Cell 37 0	Cell 38 1400	Cell 39 +2300	Cell 40 +1200	Cell 41 +9000	Cell 42 -5900	Cell 43 -9900	Cell 44 -2700	Cell 45 +2300	Cell 46 -100	Cell 47 0	Cell 48 0

Fig. 3 Design cut and fill volumes onsite

Table 3 Possible fleet combination

Fleet combination	Hauling truck type	Excavator type
1	Caterpillar 730C	Caterpillar 336D
2	Caterpillar 735C	
3	Caterpillar 740C	

The types of equipment involved in the development of the site are rollers, graders, loaders, trucks and excavators. Following the lean operation component of the established framework, the excavator is identified as the leading resource and the varying supporting equipment are the hauling trucks. The respective volume capacities of the equipment and cycle times need to be determined for configuring a fleet that maximizes the construction system's efficiency while lowering the total cost of the project. Moreover, the environmental performance of the fleet needs to be considered in equipment selection.

The fleet responsible to develop the site is composed of one roller, one grader, one loader, one excavator and an unknown number of trucks. During the work planning stages, it is determined that the fleet being considered for the project mainly varies in terms of the model of hauling trucks to be utilized. Table 3 shows the three fleet combinations being considered for the site's development.

4.2 Evaluation and Analysis

In order to determine the performance of each fleet configuration, the earthwork processes are analyzed through the application of the proposed framework, presented in Fig. 1. The framework aims to select the leanest fleet by preventing overproduction caused by unbalanced operating rates between different equipment types and by considering environmental performance as a cost factor.

The framework can also be implemented in the assessment of different construction processes. It uses simulation models and Lewis's environmental assessment for guiding equipment selection and evaluating fleet alternatives. For this specific case, the model shown in Fig. 4 is developed to perform each fleet's analysis and its impact on operational and environmental costs.

The simulation model created for this case study depicts the interactive processes for trucks, excavators, loaders and graders engaged in cyclic earthmoving operations. In this simulation model, a cycle begins by hauling trucks travelling to the site where the excavator piles up the cut soil. The speed taken by the hauling truck is determined by the effort created by the engine during travelling (engine mode). Once the truck arrives, a loader begins to fill the truck with the excavated soil, while another empty truck begins its journey towards the excavation point. After the hauling truck is fully loaded, it then travels towards a designated point to dump its load. With sufficient soil material accumulated at the designated point, a grader and a roller grade and

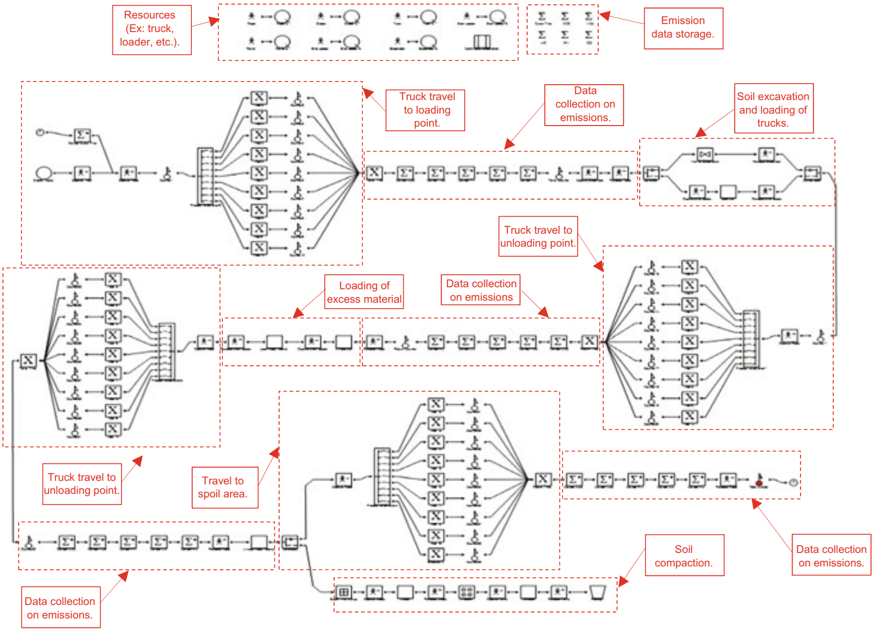

Fig. 4 Model developed in SIMPHONY to analyze different fleet combinations

compact the area. Once the hauling truck is unloaded, it then begins another cycle to haul soil.

To evaluate each fleet's performance, the model created in SIMPHONY takes the mechanical attributes of both leading and supporting equipment. Since the changing equipment of the construction system is mainly the hauling trucks, the duration to complete a cycle depends on the loading capacity, engine power and speed. Additionally, the number of trucks used in each fleet combination varies as each system aims to use the excavator (leading resource) as efficiently possible.

Lewis' methodology is implemented in the evaluation of the case study as it takes into consideration data that was collected from the field for developing mathematical equations that related energy use with emission from construction equipment. Other previously established estimating methods did not consider the impact of varying loads on the engine's production of pollutants. Additionally, Lewis' methodology allows emissions to be considered as a cost factor and a performance indicator.

It is crucial to note that the lack of data collected in Lewis' work hinders the creation of statistical distributions for emission models, as Lewis was only successful in developing an estimating methodology that used field data and considered the mechanical attributes of the equipment. The engine modes classification and the average emission measured under each engine mode provide valuable inputs in the current study for the simulation of environmental performance. Overall, the incorporation of fuel use and emission estimates in the earthmoving simulation model is effective and instrumental in determining the environmental costs associated with the use of a specific piece of construction equipment that emits large amounts of pollutants.

It is worth mentioning that one input factor that Lewis' methodology heavily relies on is the unit price set for each type of pollutant production. Note those prices are determined by individual decision-makers responsible for the assessment and their values would exert a great influence on the final environmental results derived from this framework. The set prices for the emission of each pollutant relevant to the current study are given in Table 4.

Table 5 shows that production of each pollutant varies significantly with particular fleets. While Nitric Oxide (NO_x) is the highest pollutant produced, Particulate Matter (PM) is produced considerably less. The production of each pollutant is a function of the consumption of fuel performed by each piece of construction equipment.

The overall costs resulting from the proposed framework, including environmental costs associated with each fleet combination, are displayed in Tables 6 and 7. This table shows that the fleet with 740 C trucks produces the most significant amount of pollutants, while the fleet with 730 C trucks produces the least amount of pollutant. The highest and lowest environmental costs are associated with the 740 C truck fleet and the 730 C trucks fleet, respectively. Although the fleet combination that uses 730 C trucks is associated with the highest overall cost, it is not the option resulting in the

Table 4 Set prices for each type of emissions

Pollutants	Environmental cost of pollutants ($/g)
NOx	0.0061
HC	0.0053
CO	0.0081
$C0_2$	0.0406
PM	0.0122

Table 5 Quantity of emissions produced

Fleet combination	NO_x produced (g)	HC produced (g)	CO produced (g)	$C0_2$ produced (g)	PM produced (g)
Caterpillar 730C and 336D excavator	4,600,673.20	463,607.79	1,196,682.25	401,602.81	38,234.57
Caterpillar 735C and 336D excavator	5,174,956.69	519,670.4	1,343,959.35	452,835.96	43,144.53
Caterpillar 740C and 336D excavator	5,349,911.44	536,747.17	1,388,836.78	468,442.83	44,640 15

Table 6 Final environmental results

Fleet combination	Total environmental cost
Caterpillar 730C and 336D excavator	$56,927.57
Caterpillar 735C and 336 D excavator	$64,053.45
Caterpillar 740C and 336 D excavator	66,224.35

Table 7 Case study results

Fleet combination	Overall cost
Caterpillar 730C and 336D excavator	$1,629,655.67
Caterpillar 735C and 336 D excavator	$1,496,026.20
Caterpillar 740C and 336 D excavator	$1,629,507.23

lowest duration. Hence, if a higher priority is given to the project duration, the project manager would be encouraged to select a fleet with 735 C trucks. In the case where the environmental aspect of the project is given a higher priority, then a fleet combination with 730 C trucks would be selected. These results show how each fleet combination would deliver specific benefits in terms of duration, costs and environmental impact. Additionally, it demonstrates that quantification of greenhouse emissions as a cost factor ($/g) is critical to compare emission costs to operation costs.

5 Conclusion

As the construction industry is considered among the largest consumers of natural resources and the main producer of greenhouse gases, there has been a growing concern over the negative impact that this industry has exerted on the environment [5]. The work performed in this research establishes a framework that integrates simulation and emission models to assist in the selection and use of heavy equipment. The proposed framework is intended to turn construction systems to be simultaneously lean (cost-effective) and green (environmentally conscious and sustainable). The academic contribution of this work is that the integration of simulation models with environmental assessments advances the applicability of simulation models to evaluate earthmoving operations in a more detailed and analytical manner. Additionally, the established framework aids in the development of environmental assessment models based on dynamic system simulation through generalizing the structure of the simulation model, defining model parameters and logical relationships between them. On the other hand, the developed framework clearly defines required information and system logic in environmental impact assessment of construction systems by using dynamic and interactive simulation models.

Research studies that propose a direct mechanism to quantify emissions from construction equipment is rare to find in the literature, especially a study focusing on performance analysis based on field measurement data such as Ref. [8]. The implementation of Lewis's methodology in the proposed framework is instrumental in quantifying greenhouse emissions by major equipment commonly used in heavy civil construction. At the same time, greenhouse gas emissions serve as a basis to define cost factors or performance indicators of heavy equipment. One main limitation of this research lies in the model results which only represent averages from multiple simulations and limited data from Lewis' field measurements pertaining to particular equipment (specific CAT models). With the advancements of technology, field data gathering would become practically feasible and inexpensive to scale up, resulting in more data that would enable the establishment of more in-depth and accurate statistical models in simulation.

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Identifying the Impacts of COVID-19 on Chilean Construction Projects

Felipe Araya, Leonardo Sierra, and Diego Basualto

1 Introduction

The pandemic due to COVID-19 has changed the way our society operates. Implementing social distancing policies to minimize the spread of COVID-19 has shifted most of the human activities to virtual settings, for instance, implementing online learning in educational environments such as high schools and universities. Of note, there are sectors in which routine tasks are impossible to be replaced by virtual activities, such as the construction industry. Even though the engineering stage of construction projects may be managed through virtual activities, eventually, construction workers are required to be onsite to perform the different activities needed to complete a construction project. Given this context, the construction industry has been heavily impacted by the COVID-19 pandemic by reducing the number of construction workers allowed to be onsite, so it is safe for the workers to be on the construction field, which may reduce construction projects completion rate. Additionally, from an investing standpoint, knowing that the construction industry is more exposed to the contagion of COVID-19 by requiring to have workers on the field may also disincentivize investors to develop projects due to uncertainty about the investments' return. For instance, there have been reports of construction projects being canceled or postponed in multiple countries around the globe due to the pandemic, for instance, the United States of America [14], Canada [18], the United Kingdom [26], and Chile [9].

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The construction industry plays a fundamental role in the economic development and recovery of nations as the construction sector involves large investments to develop projects, a large supply chain, and labor-intensive, which contributes to generating a large number of jobs. In Chile's case, the context of this study, the construction industry, contributes roughly 7% of the Chilean Gross Domestic Product [11]. Given this, construction related authorities and institutions have developed studies to understand the impact of the COVID-19 pandemic on the construction sector. For instance, a study from the Chilean Chamber of Construction about the impact of COVID-19 on the Chilean construction industry in 2020 found that construction and housing were the most impacted construction projects as a consequence of quarantine, conversely, infrastructure projects continued to be developed by accounting for hygiene and social distancing policies [10]. Additionally, the Chilean Chamber of Technological Development deployed a survey in 2020 and found that approximately 45% of respondents had experienced project delays or cancelation, as well as workers' transportation challenges, due to COVID-19 [12]. Further, the results from the Chilean Chamber of Technological Development's study discovered that 47% of respondents reported that although this pandemic has hit the construction industry, they expect that their companies will be able to recover.

Existing studies about the impact of COVID-19 on the construction industry have provided valuable insights about the impacts at the industry level; however, we also need studies that focus on the impacts at the project level and accounting for how the multiple stakeholders involved in construction projects are being impacted. Given this context, this study qualitatively analyzed information from 40 interviews with construction workers and professionals working on construction projects in Chile during the COVID-19 pandemic.

2 Literature Review

This literature review discusses the preliminary guidance related to the construction industry arising from the effects of the COVID-19 pandemic. According to the contributions reported on the Web of Science and Scopus databases between 2019 and February 2021, 21 studies were identified (see Fig. 1). All of them had an exploratory nature and can be organized into two areas. First, the impacts and challenges that the construction industry faces to function in the context of a Pandemic. Second, the initiatives and strategies that are proposed to minimize the spread of the virus and avoid halting construction activity.

In the first instance, the impacts and challenges of the construction industry have been focused on the administration of works and contracts. These impacts are caused directly by COVID-19 and indirectly by public initiatives to prevent its spread. In this sense, Casady and Baxter [8] analyzed the implications of COVID-19 in force majeure contractual conditions in public–private participation contracts. A case study of a highway project in Canada illustrates the failures in the contractual partnership, the need for private sector support from public agencies, the urgency to reform trust

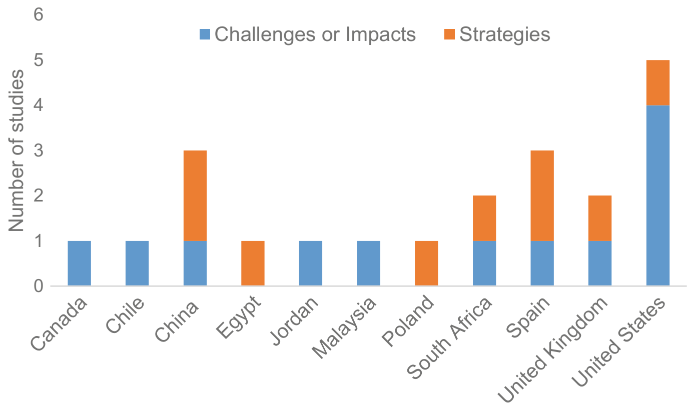

Fig. 1 Preliminary studies related to the construction industry and COVID-19, according to the WOS and Scopus databases

through non-contractual flexibilities, and the review of the medium-term requirements. Esa et al. [15] and Faust and Kaminsky [6] explored the consequences of motion control in construction sites and in the adaptation of professionals. Compliance with this regulation impacted safety, project delivery time, increased costs, reduction of work personnel, and the availability of material resources on site. Conversely, Moreno-Sueskun et al. [25], presented the positive impact of COVID-19 on the acceleration of construction projects in the United States. In this case, the reduction in traffic and the population in the cities, together with some fiscal stimuli, favored the speed in the development of construction works.

Regarding challenges placed by COVID-19 on construction projects, multiple studies have identified and evaluated risks in safety and health at work in construction sites. Some studies have proposed theoretical models that forecast the spread of COVID in construction work and in the surrounding community without considering prevention protocols [1, 3, 4, 23]. Their results predict a reduction in the workforce of between 30 and 90%, and a spread effect 5 times greater than other industrial activity. Other authors have analyzed the security conditions to avoid the spread of COVID-19; and the knowledge, attitude, and practices of professionals to lead prevention on-site. For instance, Amoah and Simpeh [2] identified that the lack of supply of personal protection elements, the lack of disinfection, the difficulty in sharing tools and equipment, and the difficulty in transporting the workforce and maintaining social distancing are key elements to insecurity in the construction industry in South Africa. Similarly, Zheng et al. [30] identified that 15% of professionals in the construction industry in China are unaware of ways in which COVID-19 is transmitted, they feel optimistic in facing the pandemic and tend to act preventively even when they must reinforce the use of the mask and the measurement of body temperature. Avice [5] and Moreno-Sueskun et al. [22] explored the security protocols for COVID-19 implemented in construction sites in the United States and Spain. Their findings showed the need to adapt the design and implementation of the protocols on site with respect to the guidelines provided by public health agencies. Even so, a higher degree of compliance is identified with respect to other industries.

On the other hand, there are studies that have proposed strategic performances to maintain the activity of the industry focused on the administration of works and workers' health. In this context, Wang et al. [29] proposed prevention policies prior to resuming work on site, social panic control, flexible management between local suppliers, contractors and clients, and enhancing the coordination skills of management teams and local governments. In addition, Raoufi and Fayek [24] suggest paying attention to workers with close labor contact with positive COVID-19, avoiding generalized fear and economic uncertainty in workers, and strengthening communication and coordination of the work team in a telematic way as strategies to maintain adequate activity on site. Complementarily, the use of technology is a strategic condition that limits social contact without neglecting the adequate performance of the members of a project. Indeed, Elabd et al. [13], Loyola [21] and Cardno [7] explored the most appropriate technologies to apply remote management of construction works. Its results do not point to a single technology, but rather to the integration of those associated with remote monitoring and evaluation of the progress of the works. In this sense, Serrat et al. [28] promotes the BIM methodology and digital processing and vectorization techniques for remote monitoring of buildings in large areas. This is accomplished through the interactive cooperation of the project team, video-drone photographic material, and inspection knowledge. Beyond strategies that allow the continuity of construction, other studies have contributed to the development of timely infrastructure to combat COVID-19. In these cases, Zhou et al. [31] reported the experience of building a hospital using modular construction in ten days, using advanced technology with BIM methodology and 5G communication. Similarly, Gbadamosi et al. [17] evaluated different emergency clinical isolation units to respond more effectively to prevent the spread of COVID-19. They proposed the design of three emergency isolation units that more effectively meet clinical requirements. These are isolation in existing disease control hospitals, isolation in adapted temporary hospitals, and isolation in newly built hospitals.

In summary, although some progress has been made in understanding and providing guidance regarding the impacts of COVID-19 and initiatives to minimize its impacts on the construction sector, existing studies have explored impacts of COVID-19 focused on specific levels of impacts, such as at the project level, at the construction workers' level. However, there is a gap regarding studies that include the impacts of COVID-19 on multiple levels of construction projects.

3 Methods

This study is focus on understanding the impacts of the COVID-19 on construction projects in Chile at multiple levels. Given the unprecedented context placed by the pandemic due to COVID-19, and that limited understanding exists about this topic, this is an exploratory study. To explore what have been the impacts of COVID-19

Fig. 2 Sequence of research method

on construction projects in Chile, a qualitative analysis is applied to data collected through 40 interviews with multiple stakeholders of construction projects in Chile (e.g., construction managers, construction engineers, and laborers of construction).

Figure 2 shows the sequence of three steps in terms of the method used to develop this study. Each step is described in the sections below. The data for this study was collected by the research team comprised of researchers from two universities, Universidad Tecnica Federico Santa Maria located in the central region of Chile, and Universidad de la Frontera, located in the southern region of Chile. The data for this study (i.e., 40 interviews) was collected between May and November of 2020.

3.1 Sampling and Interviewees' Selection

The target population for this study was stakeholders involved in construction projects in Chile during the COVID-19 pandemic context. Convenience and snowball sampling was used to contact respondents. While a convenience and snowball sampling approach may limit the capacity of this study to draw generalization about the entire population, it also allowed researchers to explore the subject under study and identify trends about the impacts of COVID-19 among different stakeholders from construction projects.

The literature suggests that for studies using qualitative methods, data should be collected until the saturation point is reached, which is when an additional interview to be collected provide minimum additional information from the data already collected [20]. Existing studies in the construction engineering and management field have reported a wide range of interviews to perform qualitative analyses. For instance, 11 interviews [19], 19 interviews [2], and 25 interviews [16]. This study collected data from 40 interviews, so this is considered to be a large enough sample by the research team. Table 1 shows the profile from the 40 interviewees, the average experience in the construction industry from the sample was 12.8 years.

3.2 Data Collection Through Interviews

A combination of online and in-person semi-structured interviews was used to collect the information used in this study. In-person interviews were done by visiting multiple construction sites to meet with the interviewees. When visiting construction sites, all safety precautions established by the project were followed to ensure the safety of

Table 1 Characteristics of interviewees' profile

Category	Description	Frequency
Geographic location of interviewee	Central region	24
	Southern region	16
Gender	Male	35
	Female	5
Position in project	Field level (e.g., workers, foreman)	20
	Engineering level (e.g., construction engineer, safety engineer)	13
	Management level (e.g., manager)	7
Experience in industry	0–5 years	8
	6–10 years	13
	11–15 years	8
	16–20 years	3
	21–25 years	3
	26–30 years	2
	31–35 years	3

the interviewee and the interviewer. In cases where interviewees were not available to meet on the site, online interviews were used.

In terms of the structure of the interviews, open-ended questions were used, and these questions asked about the interviewees' opinions regarding the impacts that the COVID-19 has had on construction projects. This format was expected to provide flexibility, so responses were not restricted in any way, and the interviewer had the option to interact with the interviewee for clarification or elaboration on opinions made by the interviewees. Interviews had a duration between 40 and 60 min. Ultimately, as the impacts of COVID-19 have placed an unprecedented context for the construction sector, using this data collection process fully supports the exploratory nature of this study.

3.3 Qualitative Analysis

The data collected from the 40 interviews was qualitatively analyzed using content analysis. Content analysis is a method that focuses on analyzing the meanings of qualitative content [27], which in this study comes from the interviewees' responses. Given the exploratory nature of this study, the content analysis is used to identify emergent categories about the different impacts reported by the interviewees. It is important to note that categories emerged through the data from the interviews, and the categories identified were not predefined by the researchers. The final sample comprised 156 excerpts that were categorized, and all valid responses were coded into the different categories to develop a coding dictionary, which provides validity and replicability to the results.

The definition of each category is shown in Tables 2, and 3 shows the definition of the multiple levels used to classify the challenges for the categories reported in Table 2. The disaggregation illustrates the impacts of COVID-19 on construction projects in Chile in multiple levels. Ultimately, the coding dictionary and coding were validated using intercoder reliability checks [27].

Table 2 Topical codes for impacts of COVID-19 on Chilean construction projects

Category	Description
Stops and delays	Statements related to halting construction projects, delays with projects under development, or in the starting of projects
Present and future financial solvency	Statements related to economic losses from construction companies, budget reductions, lack of income for companies, limited projects to be taken in the future, limited job offers, decrease in family income for workers
Productivity	Statements related to decrease in construction projects productivity and improvement of individual workers' productivity
Employment suspension and unemployment	Statements related to suspension of workers from their jobs and unemployment
Use of existing suppliers	Statements related to using pre-existing material supplies, using local material suppliers, and difficulties to find materials and services
Mental health	Statements related to mental health and family situation of workers, work environment, uncertainty about jobs, lack of concentration among workers, and pressure over workers to complete projects during pandemic context
Technical performance	Statements related to reduction of workers, hiring less qualified workers, reduction of supervision, extra managerial workload, higher risk of accidents at work due to PPE against COVID-19, communication problems
Concerns about healthy and safety due to COVID-19	Statements related to safety culture, uncertainty about individual workers' health, contagion risks, and higher attention to safety
Industry resiliency	Statements related to conditions in which projects can be developed as well as properly completed

Table 3 Levels of the impacts of COVID-19 on Chilean construction projects

Category/level	Description
Company	Statement referring to a challenge at the company level
Project	Statement referring to a challenge at the project level
Workers/professionals onsite	Statements referring to a challenge at the level of workers and professionals onsite
Suppliers/subcontractors	Statements related to a challenge at the level of suppliers or subcontractors

3.4 Limitations

It is important to acknowledge the limitations of this study. First, this study is limited to the insights received only by construction stakeholders working on construction projects in Chile during the pandemic due to COVID-19. Although the pandemic is spread all over the world and we have seen its impacts on construction industries around the globe, the impacts that the COVID-19 pandemic is placing may differ among countries, and as such, the findings of this study may be limited to the Chilean context. Another limitation of this study is that the sample had a large majority of men than women (i.e., 12.5% women); unfortunately, this unbalanced gender distribution is representative of the reality of the Chilean construction industry. Ultimately, the sample analyzed may not be necessarily representative from the whole Chilean construction industry; however, given the unprecedented challenges placed by the COVID-19 on the construction sector, this study is useful in identifying common trends and to gain insight about the impacts of the COVID-19 on the Chilean construction projects.

4 Results and Discussion

Table 4 shows the frequencies of the impacts of COVID-19 on Chilean construction projects at multiple levels; all impacts were coded into nine categories and four levels. The identification of impacts of COVID-19 on construction projects in multiple categories and at a variety of levels gives a sense of how disruptive COVID-19 has been for the construction sector.

Nine categories were identified regarding the impacts of COVID-19 on Chilean construction projects (see Table 4). These categories span multiple aspects of construction projects, such as safety, finance of project, productivity, management of the project, human resources.

The frequencies shown in Table 4 represent the level of awareness of respondents regarding the impacts of COVID-19 on construction projects. Interestingly, the category with the highest frequency was present and future financial solvency, and it received 25% of the coded excerpts (i.e., 39 out of 156). This category captured

Table 4 Impacts of COVID-19 on Chilean construction projects at different levels

Category	Levels				
	Company	Project	Workers/professional onsite	Suppliers/subcontractors	Total
Stops and delays	–	20	–	4	24
Present and future financial solvency	17	7	13	2	39
Productivity	–	24	5	–	29
Employment suspension and unemployment	–	–	8	–	8
Use of existing suppliers	–	1	–	2	3
Mental health	–	–	15	1	16
Technical performance	–	15	6	–	21
Concerns about health and Safety due to COVID-19	–	–	9	–	9
Industry resiliency	–	7	–	–	7
Total	17	74	56	9	156

impacts related to economic losses from companies, budget reductions, shortage of projects available to participate in the near future, and limited income for workers due to COVID-19. This result emphasizes the financial stress that COVID-19 has placed regarding the development of construction projects. Regarding the level of this impact, the most excerpts were coded at the company and workers/professional onsite levels. Thus, capturing that the financial impacts are not only being perceived in the operation of construction companies, but also by construction workers and their financial capabilities to face the current pandemic context.

The category with the second highest frequency was productivity, which captured 19% of the coded excerpts (i.e., 29 out of 156). Of note, the majority of excerpts coded in this category were classified at the project level (i.e., 24 out of 29). This category captured the concerns from construction stakeholders regarding the lost of productivity on construction projects due to COVID-19. The third category with the highest frequency was stops and delays, with 15% of the coded excerpts (i.e., 24 out of 156). This category captured the impacts of COVID-19 related to the halting or delay of existing construction projects as well as difficulties to start with new construction projects. In this category also most of the coded excerpts were classified into the project level (i.e., 20 out of 24).

The three categories of impacts with the highest frequencies accounted for roughly 60% of all coded excerpts (see Table 4). These three categories comprise the economic, productivity, and delays aspects of construction projects. These results capture what are the categories in which construction stakeholders have perceived the impacts of COVID-19 on construction projects the most. What these three categories of impacts may have in common is that all three captured challenges that construction projects are facing to continue being developed as before the pandemic. These categories are aligned with existing literature regarding the multiple impacts of COVID-19 on construction projects around the world (e.g., [2, 3, 4 15, 24]).

When looking at the level of influence of the impacts of COVID-19 on construction projects, 83% of the responses were coded into two levels, at the project level and at the workers/professionals' onsite level (i.e., 130 out of 156). As previously discussed, at the project level, the responses were focused on the productivity category, emphasizing that the focus of responses has been in the loss of project productivity due to COVID-19. Conversely, in this category also were discussed some positive impacts by respondents, as it was discussed that COVID-19 has also brought some improvements on the individual productivity of construction workers due to fewer distractions during the workday. These results are aligned with the study of Reid [25], who discussed that COVID-19 has also had some positives impacts on construction projects, such as the acceleration of work on critical infrastructure projects.

At the workers/professionals' onsite level, our results are also aligned with the existing literature (e.g., [24]) as the primary category of concern was the health of construction workers, namely mental health. Workers reported impacts of COVID-19 on mental health issues due to uncertainty about labor stability, problems at the individual and family level, damaged working environment, and additional pressure over workers. Another impact that was relevant, at the workers' level, was related to economic issues (i.e., present and future financial solvency). In this case, these responses captured concerns from workers related to the economic consequences that the current COVID-19 pandemic has had on their economic situation. For instance, reporting issues like loosing the primary source of family income, and limited job offers in the industry. Additionally, concerns about health and safety due to COVID-19 was the third category at the workers' level with 16% of the coded excerpts (i.e., 9 out of 56). In this case, respondents reported being concerned with the culture of safety in the project, uncertainty about the health status of other workers, contagion risks, and spreading COVID-19 from work to household members. These results reflect that workers and professionals onsite perceived the impacts of COVID-19 on multiples categories, such as impacts to the economic status of workers as well as regarding their health status.

The levels with the fewer frequencies were at the company level and at the suppliers' and subcontractors' level (see Table 4). Of note, at the company level, the coded excerpts were all categorized into one category, present, and future financial solvency. This result emphasizes that at the company level, the main impact perceived due to COVID-19 is related with the financial dimension. Regarding suppliers and contractors, the most concerning issue was related to the stop and delay of construction projects. This might be expected as the stop and delay of construction projects have a direct impact on the need from projects of materials to be supplied and the hiring of subcontractors to develop specific elements of construction projects. Important to note, the limited responses regarding the suppliers and subcontractors may be due to the limited number of participants from these groups from our sample size.

5 Conclusions

As the pandemic due to COVID-19 has stressed the construction sector worldwide, it is of paramount importance to identify the impacts that COVID-19 has had on construction projects. This study used a qualitative approach to identify the impacts that the COVID-19 pandemic has had on construction projects in Chile. By qualitatively coding the responses from 40 construction stakeholders, this study identified nine categories of impacts and organized them into four different levels. The categories with the highest frequencies referred to impacts at the economic, productivity, and managerial aspects of construction projects. These categories refer to difficulties to continue with the normal development of construction projects due to the COVID-19 pandemic. Additionally, the levels with the highest frequency of codes were impacts at the project level followed by impacts at the workers/professionals' onsite level. These results show that the impacts that construction stakeholders are the most aware of are in these two levels. This study contributes to the existing literature not only by identifying the impacts of COVID-19 on construction projects but also identified that these impacts reach multiple levels.

Future studies may expand the work presented in this study by using other instruments to evaluate the impacts of COVID-19 on construction projects, such as surveys. By using surveys, studies should collect a larger sample, but they may provide results that are statistically representative of a population, which qualitative studies cannot claim. Furthermore, conducting more interviews with more detailed classifications, or expand the geographical coverage and comparing results with similar economies/countries. Another avenue of future work is to evaluate the effectiveness of initiatives implemented by the local governments to minimize the impacts of COVID-19 on construction projects. In doing so, it would be possible to evaluate which initiatives are being more effective to minimize the influence of COVID-19 on construction projects and which ones are not. Ultimately, to include post-pandemic solutions for adjusting COVID-19 related impacts in construction projects.

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A Framework Supporting the Empirical Evaluation of BIM Assessment Models

E. Nonirit, D. Forgues, and É. Poirier

1 Introduction

Implementing BIM technologies, processes and policies is a challenging undertaking for organizations in the construction industry. Measuring the progress and performance of the implementation process is crucial in ensuring its success [16]. Maturity and competency assessment are powerful tools to help organizations take stock and manage their transformation process [20] and there is a considerable amount of research that has been undertaken in the past years on this topic [1, 3] However, throughout their development process, evaluation of these assessment models is typically limited to the development process itself [9] and often lacks external validation [17]. Moreover, in order to mitigate the challenges of a constantly evolving industry, the models developed to become standards oftentimes rely on heavy and complex evaluation mechanisms [20]. Most models are unique, propose their own measurement scale and methodology, and are therefore difficult to compare [9, 21]. Also, some of them are subjective in nature, as they rely heavily on the expertise of the evaluator to convert his opinion (subjective) into a quantifiable measure (objective) [20]. This has resulted in the development of many domain-specific models that are highly limited and contextualized to meet the immediate need of organizations in terms of evaluation [20]. This diversity of models and methods has consequences for the industry due to, for instance, the complexity of selecting a model that is appropriate for a users needs within a specific context [9].

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1.1 Overview of Research Objectives and Methodology

In this research the criteria defined by Succar et al. [18] as well as validities and concepts from the social sciences to define the basis of a tool for judging BIM implementation assessment models at the organizational level are used to evaluate different models depending on the context in which they are applied.

1.2 Overview of Results

This framework allows for the integration of the opinions of evaluators and assessed persons to visualize the strengths and weaknesses of the BIM assessment models from each point of view. The differences between these points of view can be used to identify areas for improvement for the models or to choose a model that is appropriate to the need and context.

2 Literature Review

2.1 Review and Evaluation of BIM Assessment Methods and Model

The topic of BIM implementation assessment has received considerable attention over the past years, in an attempt to identify and categorize the different approaches and potential outcomes. According to Chengke et al. [9], these detailed reviews have helped BIM users choose models that would meet their needs. Wu et al. [21] cite the reviews of Azzouz et al. [6], Giel and Issa [13], Chen et al. [8] to which we can add those of Bougroum [7], Chengke et al. [9] and finally Kassem et al. [15]. These last two present two interesting cases concerning the diversity of models reviewed and the criteria used to evaluate these models. Indeed, [15] review 25 BIM implementation assessment models including 15 BIM maturity assessment tools, 4 BIM maturity assessment methods, 3 BIM benefit assessment tools and 3 BIM benefit assessment methods. To evaluate these models, they use four sets of criteria: a complete set of criteria specific to the BIM maturity assessment tools, and a simplified version of these criteria for the BIM maturity assessment methods. A second set of criteria is used to evaluate the BIM benefit assessment tools and a simplified version for the BIM benefit assessment methods. Chengke et al. [9] evaluate nine BIM maturity assessment tools. The tools reviewed by these authors are similar in type and have several commonalities, such as the categories and indicators they assess. Chengke et al. [9] can therefore evaluate these models according to the same criteria as are easy to use, measuring scope, flexibility, validation and optimisation and benchmarking establishment. Kassem et al. [15] had very different models, so it was complex to define a single set of criteria that where precise but inclusive enough to perform a thorough evaluation. On the other hand, Chengke et al. [9] where reviewing models with the same theoretical basis so they could define common criteria to assess them. It is complex to define a single set of criteria for the evaluation of a wide variety of models but it's possible if the assessment models have a common base on which the researcher can build relevant criteria. It is important to note that some criteria have been defined in the literature specifically for BIM implementation assessment models.

2.2 Criteria for BIM Implementation Assessment Models

In their paper, *Measuring BIM performance five metrics*, [18] Succar, Sher and Williams define eleven criteria for the evaluation of the BIM implementation process regardless of the granularity level of the unit that is being assessed. To be valid, models must be accurate, applicable, attainable, coherent, cumulative, flexible, informative, neutral, specific, user-friendly and universal.

Researchers who have developed BIM implementation assessment model have subsequently used those criteria to justify the methodology or form given to their BIM implementation assessment model. Forgues [11], for example, uses these for the validation of the Supply Chain BIM Maturity Model and Giel and Issa [12] also uses the majority of those criteria for the development of their framework for assessing owners BIM implementation process.

If we compare these criteria to those used in other BIM implementation assessment model reviews at the organizational level as shown in Fig. 1, we can see that those that are broadly used within the field, inclusive of all types of assessment models, and complete in terms of the requirements being assessed. However, these criteria are not very specific and are subject to interpretation. They represent too high a level of granularity and are difficult to apply in the context of the empirical evaluation of a BIM implementation assessment model.

Beyond being domain-specific, BIM implementation assessment tools and methods are first and foremost models that have to account for a complex environment. These assessment models have the same fundamental components:

- An intent: What is being assessed and why?
- A methodology: How is the required data collected for the assessment?
- A judgement tool: How will the situation be assessed?
- Results: What information will be derived from the assessment and communicated to the assessee?
- Consequences: What will the assessor and the assessee learn from the assessment and what will be the consequences for the future?

Taking these components into account, each tool makes it possible to carry out an assessment as defined by Aubret and Gilbert [4]: "To locate evaluable objects on given scales of value, to appropriate a reference system to quantify referents" (p. 30).

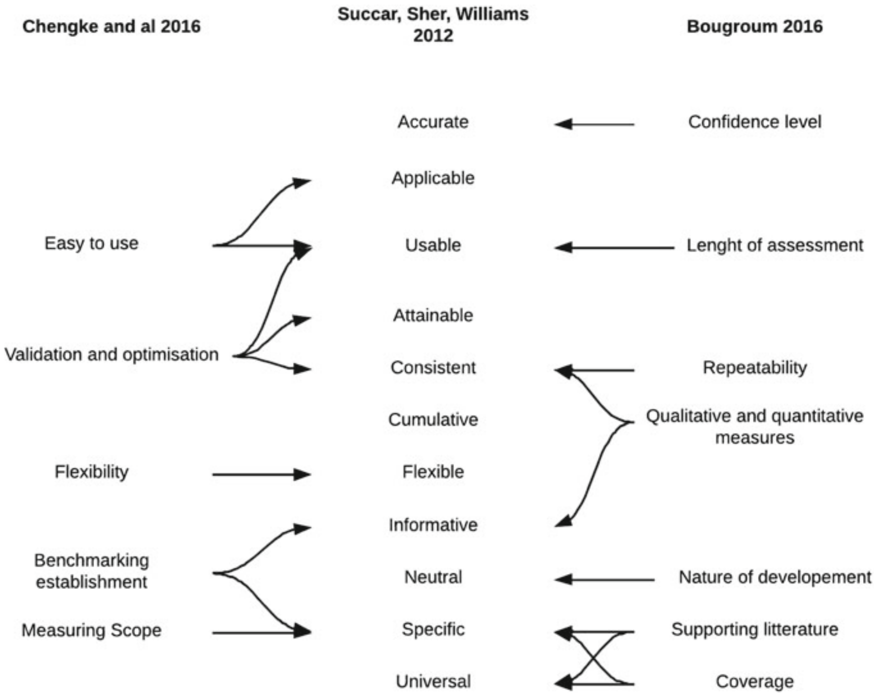

Fig. 1 Comparison of the criteria of [7, 9, 18]

In this regard, assessment is an act dependent on both the measure and its context. Few reviews of BIM implementation assessment at the organizational level take into account the context in which the evaluation is conducted and incorporate the opinions of the people being evaluated into their evaluation process. However, this is an important part of the process and it impacts the dissemination of an assessment model. In the engineering field, the study of evaluation models is mainly measurement-oriented. The types of validation and the fidelities used in engeniering research are not suitable for the evaluation of these models because they are involving evolving and multidimensional technologies and processes operating in a specific industrial environment and conducted by humans.

In the field of social sciences, researchers in psychometrics have developed many concepts to validate different type of test, particularly in relation to the context in which it the test is developed. Aspects of validation which are taken into account in this include the theoretical content of the test, from the point of view of the evaluator or the researchers (Logical Content Validity) but also from the point of view of the evaluator (Ecological Content Validity). The relationship between the test results and the theoretical construct (Criterion validity), i.e. whether, for example, a high score on a performance test for an organization will predict high performance for that organization is also accounted for (Predictive validity). Finally, the consequences of the use and application of the test, whether these are desired or not, expected or not are considered. Psychometrics also defines other concepts that may be of interest for the evaluation of BIM implementation assessment models: for example, the robustness of the test, which represents its stability to be evaluated despite unconventional situations, and its relevance, which establishes the adequacy between the test's intention and its context.

3 Objective and Methodological Approach

As part of a large-scale, multi-year effort supporting the implementation of BIM within the Province of Quebec's construction industry, the Initiative construction Québec 4.0 has been mandated to assist in the transition from traditional to BIM-enabled practices and processes. Two models for assessment of the BIM implementation process at the organizational level were identified for the creation of implementation roadmaps. The Modèle de Compétences BIM du Québec (MCBIMQ) competency assessment model based on the BIM excellence competency model and developed by Groupe BIM du Québec. And the Supply Chain BIM Maturity Model based on the OBIMA model and developed by Forgues [11]. These two models present different methodologies, criteria and constructs.

This context allowed the implementation of a research environment including academic, industrial and organizational poles to determine which model would be the most adapted to the Quebec context. Participatory action research corresponds exactly to this type of context aimed at improving policies that respond to an evolving context [19].

This action research is divided into five phases as defined by Azhar et al. [5]. In the first phase, diagnosis, the evaluation of BIM implementation assessment models in relation to their context was done through a literature review. In the second phase, action planning, the ground for two case studies was prepared. Three organizations that are advanced in their implementation of BIM technologies and processes agreed to participate in this study by assessing their BIM maturity and competencies as explained in Table 1 and provide feedback on both methods.

In the fourth phase, actions, a BIM implementation Assessment Model evaluation framework was developed. To develop the model evaluation tool, the steps established by De Bruin et al. [10] for the development of maturity models where used: (1) Define the scope of the assessment, (2) determine the basic architecture of the tool, (3) define the content of the tool, (4) test the tool, (5) deploy the tool, and (6) maintain the tool. It is composed of 44 items in total divided into 11 criteria divided into 3 categories. Of these items, 22 are intended for the BIM implementation assessor and 22 for the person most knowledgeable about BIM in the organization being assessed. The items were transcribed into questions that could be assessed on a 5-point Likert scale ranging from "no" to "perfectly". The questionnaires were then sent via a web form to the BIM directors of the organizations. The evaluation of the models was then performed through questionnaires and the analysis of the BIM implementation assessment models.

Table 1 Case studies

	Conditions	SCBIMMM	MCBIMQ	Interview and documentation	Assessed returns
Organization 1	Assessor 1, Year 2019	Yes	Yes	9 interviews, 7.3 h 11 documents 3 days on site	No
Organization 2	Assessor 1, Year 2019	Yes	No	19 interviews, 14.5 h 22 documents 3 weeks on site	SCBIMMM
Organization 3	Assessor 2, Year 2016	Yes	Yes	11 interviews	SCBIMMM MCBIMQ

Finally, the formalization of knowledge phase, the BIM assessment model evaluation tool at the organizational level was validated. For this step, the evaluation was validated through an audit of the credibility of the study established through dialogue between the various stakeholders, the transferability of the research established through the judgment of the sponsors of the evaluation, the verifiability of the research established through data traceability, and finally the confidence in the research established through expert validation.

4 Results

The first four steps of the development process behind the evaluation framework are explained bellow. The deployment and maintenance of the tool, steps 5 and 6, are not included in the scope of this research.

4.1 Development of the Judgement Tool

The first step was to define the common ground on which we would base the evaluation of BIM implementation assessment models at the organizational level. To do this, the models where defined as explained by Aubret and Gilbert [4] in their schematization of the evaluation as shown in Fig. 2.

The second step was to define the architecture of the evaluation tool. The criteria of Succar, Sher and Williams [18] being the most suitable for the evaluation of models from different theoretical bases, they served as a basis for the structure of the model. However, in order to add a layer of granularity to the evaluation, these 11 criteria were grouped into three main categories, as shown in Fig. 2,based on the three groups making up an evaluation as schematized by Aubret and Gilbert [4],

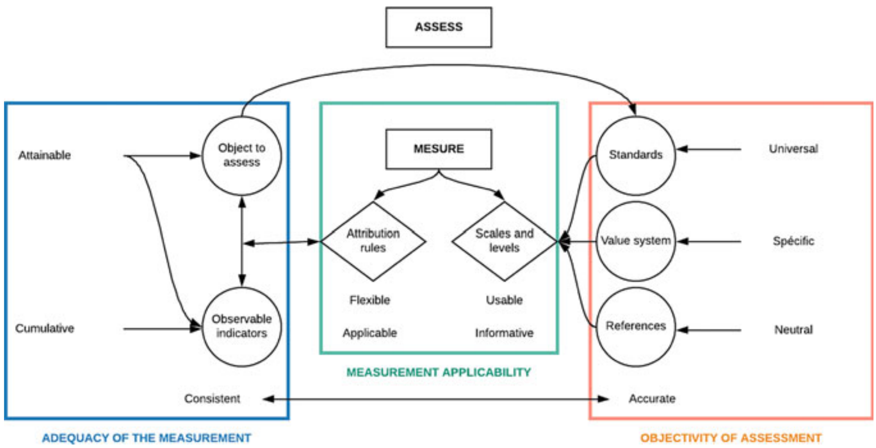

Fig. 2 Application of the criteria developed by Succar et al. [18] to the action to be evaluated as defined by Aubret and Gilbert [4]

inputs, measurement and the object to be evaluated. These three categories are as follows:

- The criteria guaranteeing the adequacy of the measure,
- Criteria to ensure the applicability of the measure,
- Criteria that guarantee the objectivity of the evaluation.

These criteria form the basis of the judgment tool as presented in Fig. 3.

The characters present at the vertices of the triangle are important for the application of the models. The criteria developed by Succar et al. [18] should help in

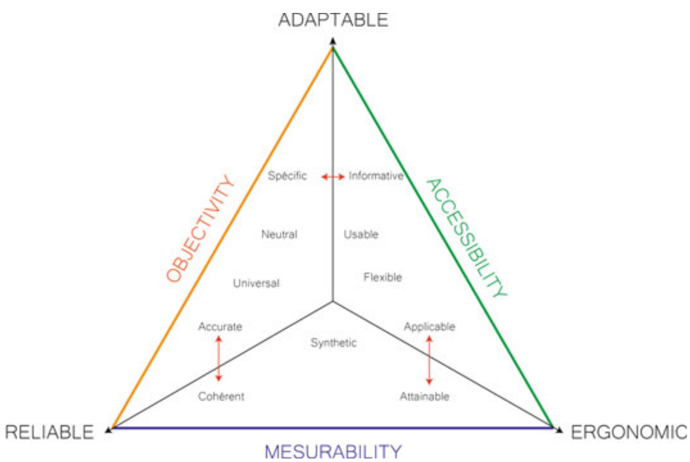

Fig. 3 Core structure of the judgment tool

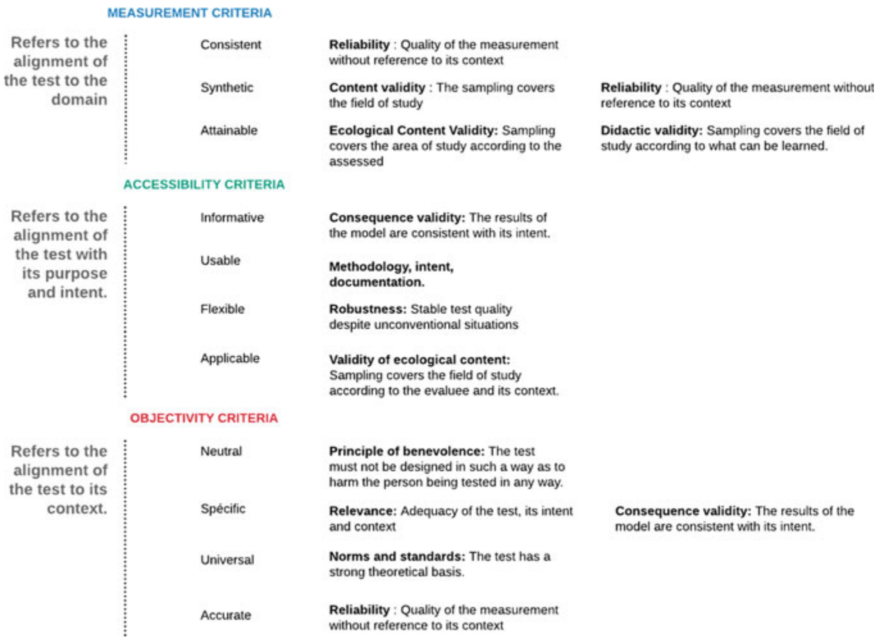

Fig. 4 Association of [18] criteria and psychometrics validities and fidelities as defined by André et al. [2] and Hogan [14]

improving adaptability, reliability and ergonomics. These characters are achievable by the interaction of criteria from two adjacent categories. The red arrows represent the interdependent criteria: Specific and informative, applicable and attainable and finally precise and consistent.

The third stage of development was the definition of the model items. To do this, we associated each criterion defined by Succar et al. [18] with one or more psychometric concepts or validity as shown in Fig. 4.

With the help of the criteria and the definition of the psychometric concepts, we defined four items per criterion. Each criterion was then assigned either to the BIM implementation assessor or to the reference person in the organization being assessed.

4.2 Testing the Model

The evaluation framework was then tested through the three organizations that agreed to participate in the case study. The evaluations and feedback from these three organizations as assessed were conducted as presented in Table 1.

MCBIMQ				
Axes	**Criteria**	**Assessed (out of 8)**	**Assessor (out of 8)**	**Gap (out of 8)**
Mesure	Coherent	6	6	0
	Cumulative	5	8	3
	Attainable	**3**	5	2
Applicability	Applicable	**3**	7	4
	Flexible	5	**4**	1
	Informative	**4**	6	2
	Usable	**3**	8	5
Objectivity	Accurate	5	5	0
	Neutral	6	8	2
	Spécific	6	8	2
	Universal	**3**	8	5
Ergonomic		4,2	6,3	2,1
Adaptable		4,4	6,8	2,4
Fiable		4,8	6,8	2

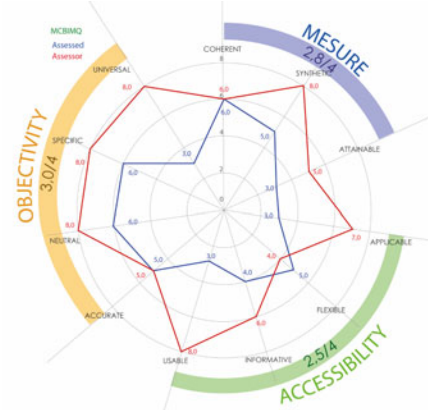

Fig. 5 MCBIMQ results

4.3 Evaluation Output Through the Framework

Figure 5 presents the results of the SCBIMMM model. These are presented in a way that puts two main measures into perspective. First, the strengths and weaknesses of the model are presented in the categories of measurement relevance, objectivity and accessibility. Second, the differences between the opinions of the assessors and those of the assessed, through the results table and the curves. The first allow to quickly visualize the possible imbalances of the model evaluated. The second allows the performance of the model to be analyzed from two points of view.

The main points that can be retained from this evaluation are that:

- The discrepancies between the opinions of the evaluators and the opinions of the evaluee are interesting to study; they reflect realities and perceptions around the model that are not necessarily visible to the researcher when reviewing the models.
- The researcher's perceptions of the usability of the model or its availability are not the same as those of the industry or the evaluators, and this can influence the dissemination of evaluation models because, for many models, the participation of the evaluee is voluntary.
- A model that is theoretically very sound may be perceived as complex to implement by the evaluators who, in their industrial context, have little time to spend studying it.

4.4 Tool Validation

In order to be validated, this assessment had to meet four main criteria: credibility, transferability, verifiability and finally trust.

The credibility of this research is established through the dialogue that took place between the Quebec BIM Group (sponsor), the researcher, the organizations evaluated, and the individuals who developed the BIM implementation assessment models studied in the case study.

Research Transferability is established by the *Groupe BIM du Québec* ongoing research feedback and final transmission in the form of a report so that they can take advantage of the proposed results.

Verifiability of the research is established by the traceability of the data collected and by the formalization of this research in the form of a master's thesis.

Finally, the confidence of the research is established by feedback from an external expert. For this validation, Dr. Bilal Succar agreed to review this evaluation. During the validation, the following points were validated. First of all, he validated the structure and development of the tool, the classification of the quality criteria of the BIM evaluation model at the organizational level as well as the association of these criteria with the psychometric validities and fidelities. At the level of the methodology and model items, the fact of gathering the opinions of the evaluators and assessors was validated as well as the interest of the strong contextual anchoring of the results. According to him, the evaluation also presented limitations. First of all, the number of criteria against which the BIM implementation assessment models and tools are evaluated are exhaustive, making it impossible to conduct an in-depth review of each criterion. Second, the tool items were not directly presented as positive, the tool had coefficients that could skew the results, and third, the limitations of the tool were not properly defined. These three points were corrected after validation. Finally, the last limitation noted during the review was the low number of responses.

The deployment and maintenance stages of the tool are not part of the scope of this research; they will be conducted during future research.

5 Discussion and Conclusion

5.1 Research Limitations

The main limitations of this research concern the sampling of respondents, the partial evaluation of the models and, finally, the testing of the tool.

First, it might be interesting to have a more diverse and larger sample and a greater number of returns in order to confirm the trends observed in this research. Second, we conducted the case studies by responding to the needs of the organizations evaluated. This allowed us to confront the evaluation models of BIM implementation with very contextually embedded situations, however, we were not able to conduct the entire evaluation for each model. For the MCBIMQ model, only the self-diagnostic part was carried out and for the SCBIMMM model, we were unable to conduct the discussion groups and process mapping. Finally, apart from the expert validation, we did not conduct any studies on the validity and reliability of the judgment tool or on the consequences of its use.

5.2 Research Contributions

This research provides two main contributions to theory. First, the empirical validation of two BIM implementation assessment models. Indeed, by conducting a case study outside of the model's development we were able to prove their relevance for the evaluation of BIM implementation at the organizational level and provide them with an empirical validation conducted within the framework of a research project, which is lacking for BIM implementation assessment models.

Then, the judgment tool developed to carry out this empirical evaluation brings a new vision of the evaluation of BIM implementation assessment models by allowing to bring them on an equal basis and to evaluate them according to the same criteria by integrating to the value system of this evaluation concepts inherent to the field of BIM implementation assessment models but also by introducing concepts from the social sciences.

Finally, it contributes to practice by providing suggestions for improvements to the BIM evaluation models evaluated, which can be taken into account by the developers of these models in order to improve them.

5.3 Future Research's

Future research will focus mainly on improvements to the judgment tool based on feedback from the validation. They will then be aimed at addressing the limitations of the present research, in particular by increasing and diversifying the tool's test sample. It could be interesting to use this tool to seek to evaluate BIM benefit assessment models for example, or to conduct BIM maturity and competency assessments of other types of organizations such as owners or contractors.

5.4 Conclusion

During this research we have noticed that the adoption of BIM implementation assessment models is dependent on their usefulness to users and also on the users' understanding of the model and its results. In addition to allowing a choice of model for large-scale implementation, empirical evaluation can help improve BIM implementation assessment models in contact with their context, possibly as part of a policy of continuous improvement.

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Integrating Building Information Modeling and Virtual Reality to Facilitate the Implementation of Universal Design for Facilities at the Conceptual Stage

Vafa Rostamiasl and Ahmad Jrade

1 Introduction

Statistics Canada [1] revealed that 16.9% of Canadians were aged 65 years or older, and 2.2% were aged 85 years or older, representing a 20.0% increase in the age of those groups since 2011. The Canadian population aged 65 years and older is expected to increase by 20.0% by 2024 [1]. A report in 2020 uncovered trends related to aging and its impact on seniors' housing aspirations, expectations, and realities across Canada. The report shows that 86% of Canadian seniors want to live in their homes for as long as they can [2] rather than going to long-term care facilities. On the other hand, on its website, Ontario's Government reported that from April 2020 to March 2021, the number of deaths due to Covid-19 in Ontario's long-term care facilities reached 3756 cases (3745 residents and 11 staffs) [3], which supports the importance of the aging in place concept. Therefore, more design strategies should be considered to overcome this issue [4] and facilitate aging in place. Universal Design aims to simplify life for everybody regardless of the age, size or ability to achieve an inclusive society where everyone has equal opportunities to participate, whether young, senior, disabled or non-disabled [5]. Here comes the term Accessibility, which is one of the critical factors for aging in place. An age-friendly design needs to be accessible for older people with varying needs and abilities [6]. It promotes seniors' physical activities and reduces the risk of many health and medical problems of particular concern to elderly Canadians. There is growing evidence that physical activity prevents or delays cognitive impairment and improves sleep [7].

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"Aging in place means having access to services and the health and social supports elderly need to live safely and independently in their homes or their community for as long as they wish or are able" [8]. To enable aging-in-place, environmental barriers must be removed, including indoor physical modifications and accommodations to enhance the accessibility and usability of the home environment, increase safety, reduce difficulties in activities' performance [9]. Physical modifications include installing ramps in staircases and safety bars in bathrooms, making premises more accessible and useable [10]. While street-level entrance, railings, automatic doors, bathroom and kitchen modifications, elevator or lift, alerting devices, and other special features are associated with the functional ability after accounting for the potential confounders [11].

Building Information Modeling (BIM) is a concept used in the AEC industry all over the lifecycle of a project, from design and documentation passing through the construction stage to operation [12].

Virtual reality (VR) provides new perspectives of visualization for designers through an immersive experience. Game engines create dynamic interactive activities to achieve an accurate and timely feedback from users' interaction with building elements in a virtual environment. Therefore, coupling BIM and VR extends BIM capabilities and makes it a more powerful tool [13].

This paper proposes a methodology to integrate BIM with Universal Design and Virtual Reality. This integration systematically incorporates Universal Design Standards into BIM environment at the conceptual design stage by using a developed database of Universal Design and Accessible Design standards to enhance BIM tool's functionalities and capabilities. It facilitates the process of retrieving universal families of architectural components by implementing UD standards into the design. Recording occupants' perceptions through their interaction with the building's design is crucial to evaluate and improve the design's usability, operability, and functionality to comply with the universal design standards. Virtual Reality Environment (VRE) is a robust method that provides designers with the ability to explore, communicate, and better understand a design. It can help them define the best practical scenario that meets occupants' requirements and permits occupants to live and walk through the building virtually before its physical construction and to do necessary modifications to meet their needs and requirements.

Therefore, the motivation of this study is to develop an automated model that incorporates UD and VR at the conceptual design stage of buildings to be used by designers to facilitate the adoption of universal design standards and processes. It simplifies the communication and interaction between owners (especially seniors) and designers to accommodate user's needs and help them age in place. Hence they are not forced to move to long-term care facilities that were among the most critical locations during the Covid-19 pandemic in terms of the virus transition and increased fatalities.

2 Literature Review

Universal Design (UD) hypothesis is to design products or environments that can be used by people of different ages and abilities without adaptation. This theory is growing worldwide and has expanded towards the scope of inclusive design, which extends the definition of UD by counting users who have been excluded by the rapid change of technology, particularly the aging population [14]. The main objective of UD is to provide inclusivity and prohibit exclusivity [15]. The term universal design was first used in the US in 1985, defined as a design approach that incorporates products and building features, to the greatest extent possible, that can be used by everyone [16]. When it comes to the UD term, many different terminologies have been used internationally, such as Accessible Design, Usable Design, Barrier-free Design and Inclusive Design. Some of these imply different ideas, while others mean the same [5]. Iwarsson and Stahl [16] describe accessibility as the encounter between the person's or group's functional capacity and the physical environment's design and demand. It refers to compliance with official norms and standards, thus being mainly objective in nature. In contrast, universal design is based on the principle that only one population comprises individuals representing diverse characteristics and abilities, and barrier-free design is perceived more negatively as it is closely related to the needs of people with disabilities [16]. The theory of UD comes with the following seven principles: (1) Equitable Use, (2) Flexibility in Use; (3) Simple and Intuitive Use; (4) Perceptible Information; (5) Tolerance for Error; (6) Low Physical Effort; (7) Size and Space for Approach and Use [15].

BIM is a concept used throughout a facility's lifecycle for visualization, scheduling, communication and collaboration among project participants. It reproduces a building's physical and functional characteristics and allows rectifying design errors or implement changes before a project is developed. BIM has received considerable attention from academia and industry because of its latent potential and capability to achieve performance improvement in the architecture, engineering, construction, owner-operated (AECO) sector [17]. Automation in the modelling process, improving the construction documents accuracy, enhancing the communication among parties in the design and reducing the field coordination problems are the most critical factors that lead to BIM adoption in a project [18]. Although there is a significant amount of research in using BIM during various project phases, limited work has been conducted about integrating BIM and UD. Coupling BIM and UD have the potential to produce high-performance and universally designed facilities.

Virtual Reality (VR) is a comprehensive technology that couples various technologies such as advanced computer technology, sensing and measuring technology, simulation technology and microelectronics technology, forming a realistic virtual world with a three-dimensional feel [19]. VR adds immersion and interactivity to three-dimensional computer-generated models by enabling architects to experiment advanced ideas compared to conventional 3D modelling tools that only visualize models in an immersive first-person [20]. The characteristics of VR technology are immersive, interactive and imaginative. Immersive includes visual and hearing immersion whereas, interactive is the user's interaction with the object and virtual scene operability, while imaginative satisfies the user's personal requirements [19]. The unique benefits of VR persuade researchers to investigate its uses in various areas of the Architecture and Construction Industry [21]. The core values of integrating BIM with VR are: (1) improving the authenticity of simulation, (2) supporting the project cost control; and (3) improving the interoperability of simulation work [19]. Therefore, this study proposes the development of an integrated model that interrelates BIM, VR and UD at the conceptual design stage of building projects to accommodate Canadians to age in them regardless of their chronicle health conditions and age.

3 Methodology

This research proposes the development of an integrated model that incorporates universal design standards and virtual reality within a BIM environment for designers to use at the conceptual stage. The integration of BIM and UD requires instant and automatic access to data and design families in order to simplify the creation of universal design for facilities. It helps designers and owners to select an optimal design based on predefined criteria. The proposed integrated model consists of various components that share data and information automatically and efficiently, as shown in Fig. 1.

Figure 2 illustrates the development process of the proposed model, which will be done over three phases. The first phase consists of developing a standard database that stores collected information and data related to UD in an attempt to simplify the process of creating universal design for proposed buildings at the conceptual stage. The second phase focuses on creating new plugins into BIM's tool (i.e., Autodesk Revit) to link the above-mentioned database and manage the selection of new families and data and information retrieval. The third phase establishes the integration7 between BIM tools and VR environments to facilitate the communication and interaction between owners and designers to meet the project's needs.

Phase 1

This phase consists of creating two databases, which are a Knowledge Database and a Family Database. To accomplish this phase, data are collected from universal design standards and accessible design standards such as the National Building Code of Canada [22] and Canada Mortgage and Housing Corporation [23]. The collected data is divided into Quantitative data and Qualitative data. Qualitative data include all the descriptive information related to objects or components in the 3D model, such as components' colour and textures, types, and associated materials. Quantitative data consists of numerical information, mainly in the form of dimensions extracted from the standards. Data are stored in tables using Microsoft Excel, which forms the Knowledge Database that holds over twelve standards collected from various sources,

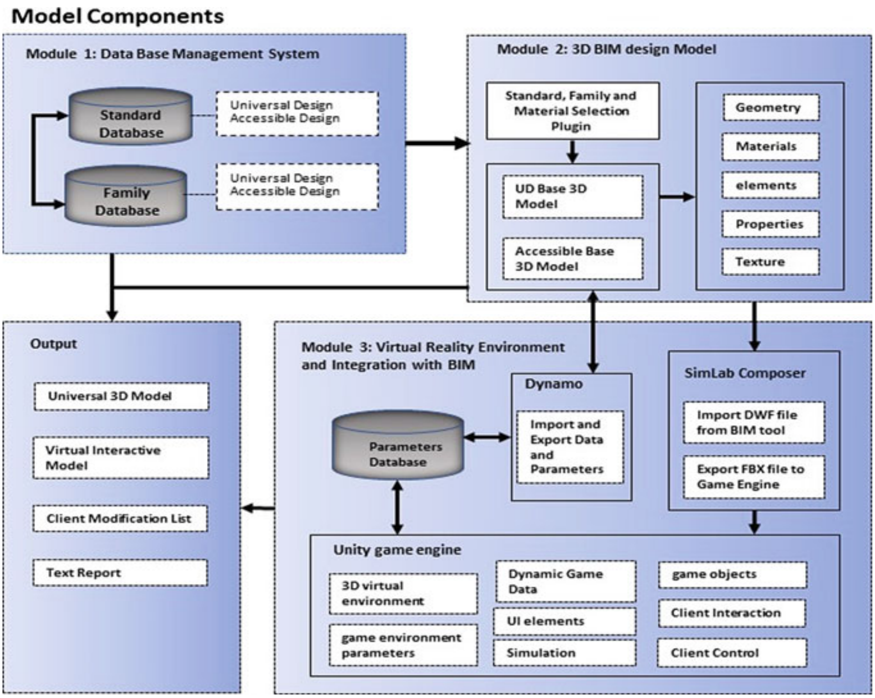

Fig. 1 Proposed model's components

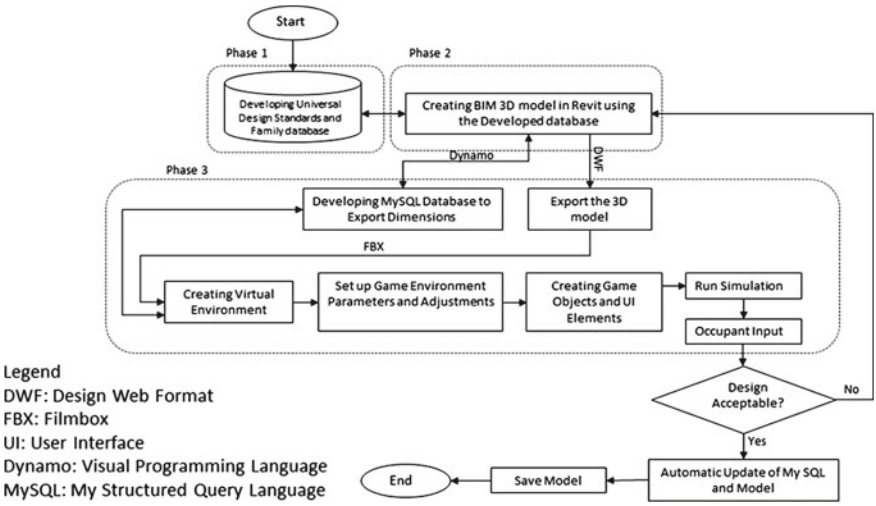

Fig. 2 Proposed model's development process

Table 1 Various stored standards in the database

Universal design standards	Accessible design standards
CMHC (Canada Mortgage and Housing Corporation)	NBCC (National Building Code of Canada)
NDA, (CNUD) The Centre for Excellence in Universal Design, Ireland	ANSI (American National Standards Institute)
Universal Design by Selwyn Goldsmith	Barrier-Free Design Guide Alberta
Universal Design Handbook, Calgary	Accessible Design Guideline, City of Toronto
	Facility Accessibility Design Standards, City of Mississauga
	Ottawa Accessibility Design Standards
	Facility Accessibility Design Standards, London, Canada
	Barrier-Free Design Guideline, City of Hamilton

as shown in Table 1. The Family Database is formed to store newly created and/or modified families by using the information and data in the knowledge database. These families are made as Revit Family (RFA) or Revit project (RVT) file formats, which are recognized by BIM tools (i.e., Autodesk Revit) and are stored in the corresponding database. Designers can select a specific standard from the created database. Once the standard is selected, its related families are loaded in a pre-defined path linked to BIM tool's library. The significant contribution of the developed database is to enhance the functionality and capability of BIM tools at the conceptual design stage.

Phase 2

This phase concentrates on customizing BIM tool to incorporate the databases of phase 1 and to accommodate the proposed model's UD requirements. This phase starts by creating new plugins in BIM tool and linking them to the developed database to manage and ease the selection and retrieval process of the new families that will be used while creating the 3D models of proposed buildings. Upon starting the design process, designers directly access the various universal design standards and associated families through the created plugin. Designers can view, download, share and print these documents easily and instantly.

The customized families will also be loaded in the predefined library of BIM tool so that designers can use them to select the most appropriate family while modelling the proposed project.

Phase 3

One of the significant obstacles perceived in the existing design process, especially for aging practices, is the lack of adequate design communication for clients to understand the design intention [24]. Therefore, this phase focuses on integrating BIM and VRE for better communication and interaction between users and designers.

The development of VR applications in a game engine environment provides an immersive experience for users [25]. Therefore, four major steps are taken for this integration: (1) model transfer, (2) data transfer, (3) database development, and (4) user interface design. The first step aims to transfer the 3D model from BIM tool to the game engine for further development, which is one of the most prominent challenges designers would face. However, Autodesk Revit, as a BIM tool, supports various 3D file formats such as DWF and FBX. Exporting the 3D model directly to the game engine leads to have data, such as material properties and textures, being lost during the transition, which necessitates having them configured manually in the game environment. To reduce data loss, middleware tools (i.e., SimLab Composer and Autodesk 3ds Max) can be used. For this study, SimLab Composer is selected because it supports various 3D file formats. For that reason, 3D models are transferred as DWF files to the middleware tool and then as FBX files to the game engine.

The second and third steps consist of developing a separate database and transferring specific data, such as components' dimensions, from BIM tool to the database linked to the game engine. That database links BIM tool and the game engine by allowing two-way data transfer between them. MySQL is used to create the database, then an object-oriented programming language (i.e., C#) is used to create a code that automates the data transferring process. To link the database to BIM tool, Dynamo visual programming is used. Data such as dimensions, names and ID numbers of the components used in the 3D model are stored in that database and are used in the game environment. Any users' input or alteration in the game environment will be automatically updated in the database and then in BIM tool library.

The fourth step focuses on creating a virtual environment and setting up the game environment parameters and adjustments, such as adding an avatar and a camera. The camera is placed at the user's eyes' height and modified based on its size to provide a realistic experience. The avatar is adjusted to be able to collide with the objects. Therefore, the avatar can walk, run, or go up and down the stairs without falling through them. To achieve a collision effect, a collider needs to be added to the avatar and the objects that the user might run to [25]. The most important part of this step is the creation of a communication panel by using the User Interface (UI) elements. This panel is designed for the 3D model components, such as doors, windows, stairs, railings cabinets, besides showing detailed information, such as objects' names, IDs and dimensions based on BIM tool database. A virtual keyboard is added to allow users to modify the object dimensions instead of using the physical keyboard.

Game engines such as Unity have the ability to create apps for Android, iOS, and Windows easily. Therefore, users who are not familiar with game engines can quickly and efficiently communicate with the 3D model and modify the model based on their needs. Routed on that modification, the database and 3D model in BIM tool will be updated automatically. This automation will significantly reduce human errors and minimize the associated time and cost.

4 Model Testing

To test the developed model and examine its performance, a single-floor residential building is used. Autodesk Revit is used as BIM tool, and the building's 3D model is created with all the geometry of its components such as walls, doors, windows, floor, stairs, cabinets, and railings. During the 3D model development, the families stored in the external database are retrieved by using the newly created plugin in Autodesk Revit. This plugin allows the designer to select an appropriate standard from various options stored in the database. It would also enable the designer to read the documents, compare different standards, check the created components based on the selected standard, and use the associated family to implement the selected standard into the building's 3D model. Figure 3 illustrates a snapshot of the created plugin and its use during the design process.

In order to integrate BIM with a game engine, the 3D model is transferred from Autodesk Revit to Unity Game engine by using SimLab Composer as a middleware tool. A database is then created in MySQL using Dynamo visual programming, which automatically imports and exports data from the MySQL database. This database is the link between BIM tool and the Game engine.

By setting up the VR environment and making some adjustments to the 3D model, the user is able to walk through and explore the designed building. By setting up more adjustments for doors, doors will be opened when the user moves toward them and will be closed when he/she moves away. Therefore, the user can explore the building

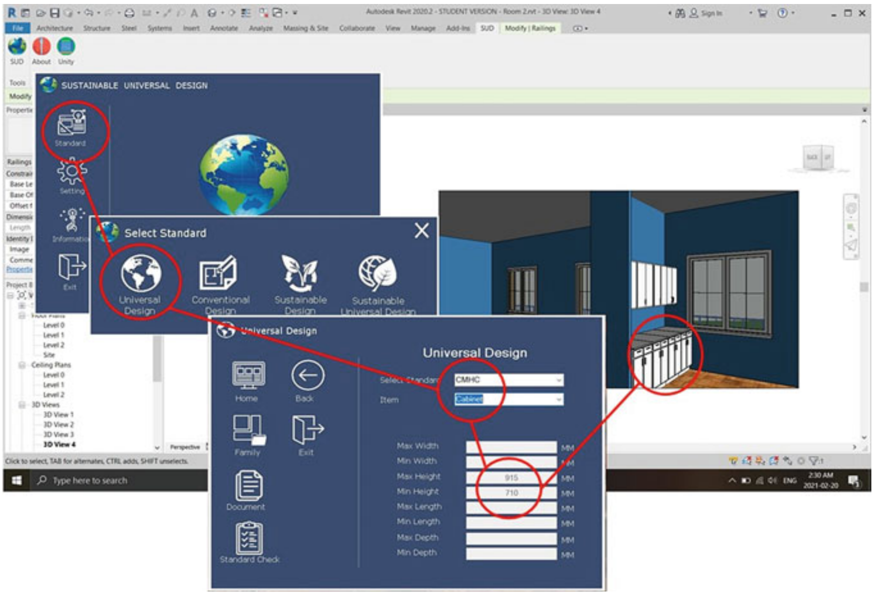

Fig. 3 Snapshot of the created plugin and 3D model

from the outside, can move toward the entrance, and then go inside and walk into the building. The communication panel allows users to enter their input into the 3D model by clicking on each item, as shown in Fig. 4.

Upon the user modification through the communication panel, data in the MySQL database and Autodesk Revit are automatically updated. Figure 5 shows the integrated

Fig. 4 Snapshot of the communication panel in the game engine

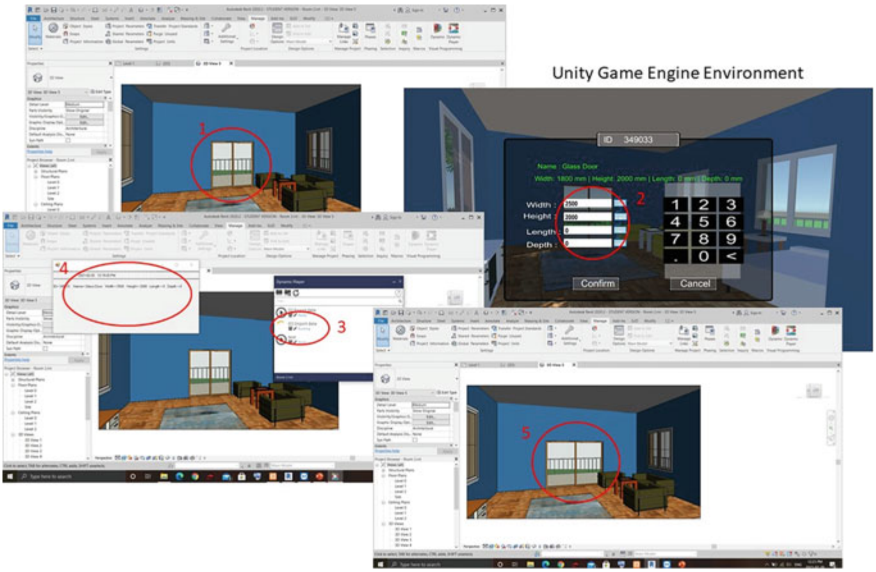

Fig. 5 BIM-VR integration

automation: (1) a door in Autodesk Revit with original dimension (1800 mm width and 2000 mm height); (2) communication panel in the game engine environment and the associated data for the selected door. The width of the door is changed from 1800 to 2500 mm; (3) importing the data from MySQL by using Dynamo visual programming; (4) a text report shows the last updates; (5) automatic update is done in Autodesk Revit. This process is examined for other items such as windows, railings, cabinets and furniture. The results are impressive. With no extra time and effort, all objects are instantly modified in Autodesk Revit.

5 Conclusion

This paper presented a part of more comprehensive and ongoing research and described the developed integrated model with its several BIM-based processes. The novelty highlighted in this study resides in the integration of Universal Design with Building Information Modeling through an automated process by creating a new plugin to assist designers incorporating UD standards into the design of proposed buildings at the conceptual stage in a timely and cost-effective way. By integrating BIM and VR, designers and occupants can experience a better and effective communication channel through an immersive interactive environment. This study focuses on the conceptual design stage of buildings, where designers need to access important information to select the appropriate UD standard to implement it in the project and to communicate their design with the occupants to meet their satisfaction and needs to reduce future modification and alteration, which minimize the associated cost. Adopting UD principles early during the design stage leads to buildings that permit seniors to age in their home rather than going to long-term care facilities where they are at higher risk of being affected by situations such as the Covid-19 pandemic in the future.

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