AN ABSTRACT OF THE DISSERTATION OF

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Title: Application of Technologies for Temporary Structures during the Design and Construction Phases

Abstract approved:

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John A. Gambatese

The development of technologies such as Building Information Modeling (BIM), light detection and ranging (lidar), and sensor-based systems poses new opportunities for researchers to rethink how construction safety and health can be approached during the design, planning, and construction phases of a project. Nevertheless, the majority of the technology applications developed to date have focused on permanent structures rather than temporary structures. Due to the "temporary" nature of temporary structures, stakeholders might easily underestimate their importance and not pay adequate attention to them in comparison with permanent works. But temporary structures are extensively used, associated with high rates of injuries and fatalities, and nearly three-fourths of the construction workers in the US perform construction activities on or near temporary structures. There are considerable needs to improve the performance of temporary structures.

The overarching goal of this research is to advance the body of knowledge and make practical contributions to the integration of temporary structures with advanced technologies. Specifically, this research explores the identification of the desires and needs of adopting technologies in temporary structures, and the development of tools to improve the quality of temporary structures in the design and construction phases of a construction project. To attain the research goal, the study firstly investigated the current design and inspection practices for temporary structures, as well as professionals' viewpoints of applying technologies on temporary structures by surveying professionals who are familiar with temporary structures and construction technologies. Based on the results of this first step, the study proposed tools to remedy the current deficiencies in design and inspection quality of temporary structures discovered. The type of temporary structure targeted in the research is concrete formwork systems, especially formwork for concrete slabs. For the design and planning phases, a BIM plug-in was developed in Revit using C# to achieve automation in designing and modeling temporary structures with safety considerations. For the construction phase, a wireless sensor-based formwork monitoring system was proposed and developed to improve the inspection quality during concrete placement. The present research contributes to the body of knowledge by identifying the needs and desires of using technologies in temporary structures, as well as the technology selection criteria and areas of improvement for temporary structures, and develops practical tools to improve the design and inspection quality of temporary structures.

Application of Technologies for Temporary Structures during the Design and Construction Phases

by

Ziyu Jin

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APPROVED:

Major Professor, representing Civil Engineering

Head of the School of Civil and Construction Engineering

Dean of the Graduate School

Ziyu Jin, Author

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DEDICATION

To my mum and dad

1. INTRODUCTION

The architecture, engineering, and construction (AEC) industry is currently experiencing rapid growth. More construction workers are being hired to accommodate the need for new infrastructure projects. According to the U.S. Bureau of Labor Statistics (BLS, 2021a), in February 2021, more than 7.3 million employees were working in the construction industry in the US. However, based on the workforce statistics, the safety record for construction has been poor. The total number of recordable cases of nonfatal occupational injuries and illness in the construction sector was 200,100 in 2019, accounting for seven percent of all private industry nonfatal injuries and illnesses (BLS, 2020). In terms of work-related fatalities, as shown in Figure 1.1, 1,061 workers died in the construction industry in 2019, which is substantially greater than the number of work-related fatalities in other industries (BLS, 2021b). That being said, compared to other occupations, construction laborers are more likely to get injured or killed - one in five worker deaths in 2019 were in construction (OSHA, 2021). The fatal work injury rate in construction was 9.7 fatalities per 100,000 full-time equivalent workers in 2019 (BLS, 2021b).

The hazardous conditions in the construction industry could be attributed to its unique nature, workers' unsafe behaviors, and poor safety management and organizational safety climate and culture (Jannadi and Bu-Khamsin, 2002; Tam et al., 2004; Törner and Pousette, 2009; Swuste et al., 2012; Li et al., 2015). Construction sites are often subject to harsh working environments (e.g., noise, vibration, extreme weather conditions, etc.) and constant change (Jannadi and Bu-Khamsin, 2002; Tam et al., 2004). The work tasks are physically demanding, and the operations require the involvement and coordination of multiple parties, such as contractors, sub-contractors, designers, suppliers, and owners. Investigating the causes of accidents and exploring ways to prevent occupational injuries and illness with an objective to improve the overall safety and health in the construction industry has been of interest to many researchers both past and present.

Swuste et al. (2012) reviewed construction safety literature in the building sector from 1980 onwards. By summarizing causes of accidents in the construction industry, Swuste et al. (2012) stated that construction safety should be addressed at the organizational and individual levels, and during the design phase. Covering a wider spectrum of research topics on construction safety, a review conducted by Zhou et al. (2015) found that the construction safety literature was centered on two aspects: management-driven studies focused on enhancing management performance, and technology-driven studies focused on using various types of technologies to address construction safety concerns. In 2019, utilizing a scientometric analysis approach, Jin et al. (2019a) reviewed 513 journal articles on the topic of construction safety. The findings indicate that the articles within the recent decade put more attention on applying technologies, such building information modeling (BIM), virtual reality (VR), and data analytics in the field of construction safety management.

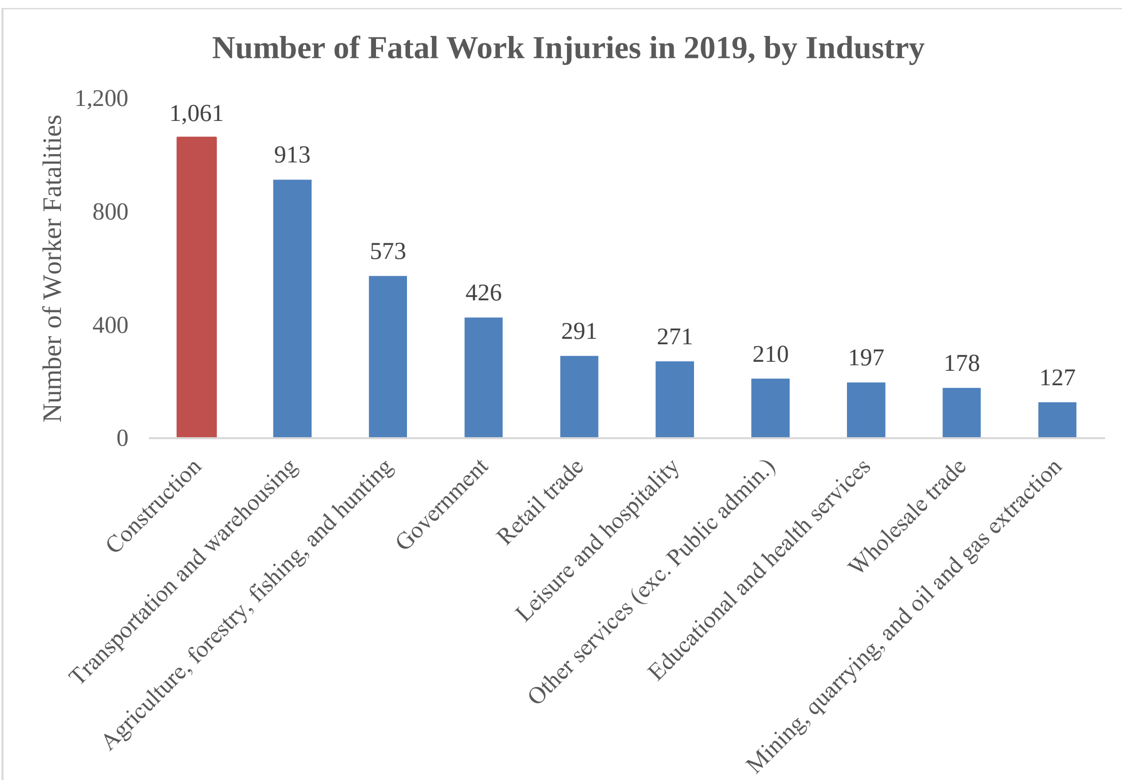

Figure 1.1. Number of Fatal Work Injuries in 2019 (Adapted from BLS (2021b))

By all means, the use of technologies to enhance construction worker safety and health has become a growing trend in recent years (Zou et al., 2017; Jin et al., 2019a), and it could be an effective and innovative approach to support construction management (Lingard, 2013; Zhou et al., 2013).

1.1 Background

1.1.1 Technology Applications for Construction Safety and Health Management

Advanced technologies have revolutionized the project delivery process in the construction industry, from the predesign phase all the way to the post-construction phase. Recent studies have highlighted the vital role of various types of technologies in managing safety and health issues in construction projects.

BIM has been used extensively for the design, planning, construction, and operation phases as it offers a visual representation and integrated platform for all stakeholders to collaborate (Azhar, 2011). Prior research studies (Zhang et al., 2013; Guo et al., 2017; Zou et al., 2017; Martínez-Aires et al., 2018; Akram et al., 2019; Jin et al., 2019b; Yuan et al., 2019) have shown how safety could be effectively incorporated and addressed using BIM-based tools in the design and planning phases. BIM has been widely used for hazard recognition and prevention, and worksite safety planning. The visualization feature offered by BIM is identified to be the most promising feature to improve safety management (Akram et al., 2019). By integrating with unmanned aerial vehicles (UAVs), the work conducted by Alizadehsalehi et al. (2020) has shown BIM's potential to enhance safety practices through real-time safety data collection using UAVs during the construction phase. Other visualization technologies such as computer-aided design (CAD), VR, and augmented reality (AR) offer a better way to present and visualize safety-related project information, conduct hazard identification and management, and assist on-site safety inspection (Guo et al., 2017; Li et al., 2018).

Localization and tracking sensing techniques such as radio frequency identification (RFID), ultra-wideband (UWB), ultrasonic sensors, and global positioning system

(GPS) could be used to detect and track moving machines, workers, or materials. The captured information would help in preventing accidents by generating warnings to gain workers' attention (Soltanmohammadlou et al., 2019; Wong et al., 2019). To fully benefit from the real-time data captured by sensors, wireless sensor networks (WSN) and internet of things (IoT) offer the possibility to turn data stored in a passive manner for proactive safety and health management. With the use of WSN, the sensor nodes collect physical or environmental data in different locations, then the data are transmitted and processed in a terminal server via a network. The analyzed data could be utilized for the automatic identification of hazards. For instance, Chan et al. (2020) proposed to integrate a microcontroller, GPS, an inertial measurement unit (IMU) and UWB for an improved hazard proximity warning system. The positions of construction workers and equipment were continuously tracked by the system, and when the system detected that the two entities were too close to each other, a warning was sent to both entities to inform them that a potential hazardous situation may occur.

With the development of computer science, particularly, machine learning and computer vision in image processing, the information captured by digital cameras and light detection and ranging (lidar) can read, analyzed and interpreted by specific algorithms. Vision-based sensing techniques have been considered to be effective solutions complementary to the current time-consuming and subjective manual observational practices (Seo et al., 2015). Such applications include but are not limited to: construction operation monitoring, unsafe worker behavior detection and monitoring, and structural health monitoring (SHM) (Seo et al., 2015; Ye et al., 2016; Fang et al., 2020).

The adoption of wearable technologies for personalized construction safety and health monitoring has received substantial attention in recent years. Wearable technologies are based on a wide range of different technologies such as RFID, ultrasonic sensors, Bluetooth, electrocardiogram (ECG/EKG), and electromyography (EMG). Benefiting from the rich information obtained by the technologies, wearable technologies can be used to monitor and measure safety and health performance metrics to improve the accuracy of hazard detection through physiological monitoring, environmental sensing, proximity detection and location tracking (Awolusi et al., 2018; Ahn et al., 2019; Nnaji et al., 2021).

Other technologies such as geographical information systems (GIS) have been utilized to assist on-site monitoring and control of operations (Cheng et al., 2002) and safety planning (Bansal, 2011). GIS provides the possibility to consider environmental issues such as site topography, thermal comforts, and access route planning that also have impacts on worker safety (Bansal, 2011). Table 1.1 presents a summary of the previous review studies that discuss technology-based solutions for construction safety and health management.

Generally, the use of a variety of types of technologies has provided a more accurate, reliable, and efficient way to handle numerous tasks related to construction safety and health management than when using traditional manual practices. Nowadays, technologies play active roles in hazard identification, risk assessment, risk control and safety training in the construction industry. Key stakeholders involved including owners, designers, construction managers and workers could all benefit from the improved technology-based approaches throughout the project delivery process.

Table 1.1. Previous Review Studies about Technology Applications for Construction Safety and Health Management

Authors (Year)	Focused Technologies	Findings
Zhou et al. (2012)	Databases, VR, GIS, 4D CAD, BIM and sensing technologies	• The investigated digital technologies were used to develop applications to improve construction safety at various levels, including project, product, process and operation levels, and are useful in providing visual aids and conducting effective communication to manage site safety risks. • The developed tools mostly focused on addressing risks in the construction phase; only a few of them attempted to deal with risks in the design phase. • Future research studies could be conducted to: 1) investigate the relationship between construction safety and the use of digital tools, and 2) develop tools and processes for interdisciplinary collaboration and information sharing.
Zhou et al. (2013)	Information communication technology, sensor-based technology, RFID and VR	• Technological applications mainly focused on reactive safety management (e.g., hazard identification, safety assessment and cause analysis) in the past. • The recent applications shifted the focus to emphasize proactive safety management (e.g., design for safety, safety monitoring and safety information). • The integration of information collection technology and visualization technology with safety management enables real-time construction safety information collection, distribution and visualization. • Future research studies could be conducted to: 1) extend the scope of technology applications to the entire life cycle of a construction project; 2) conduct research studies to evaluate the relationship between technology utilization and safety performance, as well as the cost-effectiveness of the application; 3) make transitions from research into practice; and 4) consider legal issues with the technology applications.

Table 1.1. Previous Review Studies about Technology Applications for Construction Safety and Health Management (Continued)

Authors (Year)	Focused Technologies	Findings
Seo et al. (2015)	Computer vision technique	• Based on information required to assess unsafe conditions and acts for scene-based, location-based, or action-based risks, computer vision applications for construction safety and health monitoring can be categorized into three groups: 1) object detection, 2) object tracking, and 3) action recognition. • The identified research challenges exist in: 1) comprehensive understanding about the site in a safety context, 2) the quality, reliability and accuracy of data collected, and 3) object and action recognition with multiple equipment and workers presented. • The practical and practical issues are: 1) lack of task-specific and quantifiable metrics to evaluate unsafe conditions and acts, 2) lack of comprehensive image datasets with diverse viewpoints of construction sites, and 3) privacy concerns with continuous monitoring at construction sites.
Zhang et al. (2017)	Sensor-based technology, including sensor-based location, vision-based sensing, and wireless sensor networks, etc.	• The main applications of sensor-based technology are accident prevention, safety design, hazard identification, integrated safety management, structural health monitoring, safety training and education, accident forewarning system, and highly dangerous operation management. • Based on the identified gaps within the existing research studies, future work could be conducted to: 1) include multiple sensor-based technologies, 2) expand information dimension and increase data utilization, 3) apply proposed sensor-based applications to real construction environments, 4) control hardware cost and simplify software development and process, and 5) utilize smartphone for the applications.

Table 1.1. Previous Review Studies about Technology Applications for Construction Safety and Health Management (Continued)

Authors (Year)	Focused Technologies	Findings
Zou et al. (2017)	BIM and BIM-related technologies (e.g., database technology, VR, 4D CAD, GIS, etc.)	• BIM and BIM-related tools have been used to identify and prevent risks in early stages of a project, and to facilitate effective communications among project team members. • BIM could be used to support systematic risk management in the project development process, and could also be used as a central data terminal and platform which enables interactions with other BIM-related tools. • The current research studies placed a primary focus on investigating technical developments, and a few of them were used or implemented in real workplaces. • Future research could be conducted to: 1) prompt multi-disciplinary system-thinking, 2) develop and implement a method and process that are effective in real projects, 3) integrate traditional methods with BIM and BIM-related technologies for risk management, and 4) implement BIM-based risk management in the design process.
Guo et al. (2017)	Visualization technology (e.g., BIM, 4D CAD, VR, AR, etc.)	• Visualization technology could be used during the pre-construction phase, mainly for safety training and job hazard identification and management, and could also be used during the construction phase for on-site safety monitoring and warnings. • The shortcomings of the reviewed studies include the lack of a comprehensive safety training approach with technology, limited safety hazards considered in technology applications for safety management, and technical and practical issues with technology applications (e.g., low accuracy, disruption to operations, etc.)

Table 1.1. Previous Review Studies about Technology Applications for Construction Safety and Health Management (Continued)

Authors (Year)	Focused Technologies	Findings
Li et al. (2018)	VR and AR	• Use of VR/AR in the safety management domain provides opportunities to conduct more effective hazard identification, safety training and education, and safety inspection and instruction than traditional methods. • Future research could be conducted to: 1) include more construction engineering knowledge when developing safety tools with VR/AR, 2) develop standards or requirements for VR/AR applications, 3) address safety issues from the perspectives of ergonomics and psychology, and 4) assess workers' immediate reactions and responses with VR/AR environments.
Awolusi et al. (2018)	Wearable technology	• Wearable technology systems and sensors are promising for applications in identifying and addressing construction safety and health hazards through physiological monitoring, environmental sensing, proximity detection, and location tracking. • Future research is recommended to integrate multiple devices and sensors into a wearable device for effective personalized safety monitoring.
Martínez-Aires et al. (2018)	BIM	• BIM applications in the safety management domain mainly focus on construction or safety management, 4D schedule and planning, visualization/simulation, collaboration and communication, and hazard identification. • Future research could be conducted to: 1) integrate BIM with other technologies, for which additional attention should be paid on data interoperability, and 2) develop and improve BIM implementation standards.
Edirisinghe (2019)	Smart sensor technologies	• Current digital skin research could be categorized into two aspects: 1) applications that use context-aware information visualization, and 2) real-time tracking applications. • The challenges that inhibit the technology application on sites exist in technology limitations, technology acceptance, technology diffusion, standardization of technologies, and economic challenges.

Table 1.1. Previous Review Studies about Technology Applications for Construction Safety and Health Management (Continued)

Authors (Year)	Focused Technologies	Findings
Antwi-Afari et al. (2019)	Sensing and warning-based technology	• The reviewed sensing and warning-based technology applications can be categorized into six main research topics: 1) construction site safety management and monitoring, 2) safety risk identification and assessment, 3) intrusion warnings and proximity detection, 4) physiological status monitoring, 5) activity recognition and classification accuracy, and 6) structural health monitoring. • Future research is recommended to: 1) explore the possibilities of applying sensing- and warning-based technologies in the total life cycle of a construction project, 2) develop small, lightweight, and reliable wireless sensors for construction workers, 3) prompt the transition from research to practices, and conduct cost-benefit analysis for technology applications, and 4) integrate sensing and warning-based technologies with other advanced information technologies.
Soltanmohammadlou et al. (2019)	Technologies related to real-time locating (e.g., GPS, UWB, RFID, etc.)	• Major research topics related to real-time locating systems for safety management include safety monitoring, accident prevention, behavior-based safety, safety alerts and warnings, ergonomics analysis and physiological status monitoring, communication-based safety, and on-site safety training. • Future research could be conducted to: 1) explore efficient and cost-effective technology options in different safety scenarios to advance construction safety management, and 2) assess the long-term effectiveness and efficiency of adopting technologies for safety and health purposes.

Table 1.1. Previous Review Studies about Technology Applications for Construction Safety and Health Management (Continued)

Authors (Year)	Focused Technologies	Findings
Akram et al. (2019)	BIM	• The most frequently used elements of safety in the application domain of BIM are hazard recognition, hazard prevention, and worksite safety planning. • The visualization ability offered by BIM is identified to be the most promising feature to improve safety management. • Future research is recommended in: 1) providing safety training using BIM to fully utilize its virtue of visualization feature, 2) investigating financial impacts of adopting BIM for safety improvement (e.g., cost required for technology investment, training and personnel wages, investment payback period, etc.), and 3) incorporating other sensing technology with BIM for real-time decision support for safety-related matters.
Ahn et al. (2019)	Wearable sensing technologies (e.g., motion sensors, physiological sensors, etc.)	• Wearable sensing devices are used to address five main construction safety and health issues; they are musculoskeletal disorders, falls, physical workload and fatigue, hazard-recognition abilities, and workers' mental status. • The identified challenges in the use of wearable sensing technologies for the application are: signal artifacts and noise in the obtained measurements, inconsistent standards in assessing safety and health risks, user resistance in technology adoption, and uncertainty about the financial impacts of technology adoption. • Future research is recommended in: 1) exploring advanced filtering methods and sensor fusion for wearable applications, and 2) developing business cases to demonstrate the effectiveness of the tools, and to learn about the costs, benefits, and other long-term tangible or intangible impacts, thereby prompting the application of wearable sensing technologies in the domain of construction safety and health management.

Table 1.1. Previous Review Studies about Technology Applications for Construction Safety and Health Management (Continued)

Authors (Year)	Focused Technologies	Findings
Mihic et al. (2019)	Innovative technologies (e.g., BIM, GIS, VR, AR, sensing technologies, database integration, knowledge-based systems, etc.)	• The most cited technology used for construction health and safety management is BIM, followed by the database and AR. • These innovative technologies are mostly used for hazard identification, followed by design for safety suggestions. • The identified research gaps within the previous studies are: the neglect of technology usage in earlier project phases (before the construction phase), minimal attention to construction activity and task levels, lack of studies on infrastructure projects, and limited coverage of types of hazards
Fang et al. (2020)	Computer vision	• In the worker behavior-based safety domain, computer vision techniques have been applied to identify when workers are not wearing their required personal protective equipment (PPE), whether workers are exposed to hazardous areas, and whether workers follow safety procedures. • The challenges of using computer vision to identify unsafe behavior include: lack of training data and standards of performance evaluation, limitations in generalization, and inability to detect small or hidden objects and extract multiple features to identify unsafe behaviors.
Asadzadeh et al. (2020)	Sensor-based technology (e.g., WSN, RFID, UWB, and vision-based techniques) and BIM	• Sensor-based technologies have been applied to various aspects of safety risk management, including hazard identification, risk assessment, control risks, and review control measures. • The integration of sensor-based technologies with BIM could improve safety management in construction as BIM provides many ways to address safety, such as knowledge management, safety planning, design for safety, and real-time safety monitoring. • Future studies could be conducted to: 1) investigate ways to identify and document near-miss incidents, 2) develop decision support platform, and 3) explore applications that integrate vision-based monitoring systems with BIM.

1.1.2 Temporary Structures and Their Failures

As described in the previous section, technologies have changed the ways that professionals deal with construction safety and health hazards during the design, planning and construction phases. The primary foci in previous research is permanent structures – structures that are designed for a long-term use, such as floors and walls (Mirzaei et al., 2018). However, structure failures occur more often during the construction phase than when they are in service, because many of such failures occur as a result of the failure of temporary structures (Ratay, 2004).

The term “temporary structures” has been defined as: 1) systems and assemblies used to temporarily support permanent work (e.g., formwork, cofferdams, earthwork sheeting, shoring, etc.); 2) systems and assemblies that serve as platforms for construction workers (e.g., scaffolding, ramps) during construction; and 3) structures built for a temporary purpose (e.g., temporary tent, temporary entertainment structure, etc.) (Jung, 2014; Yuan et al., 2016). The types of “temporary structures” focused on in this dissertation are the first two types of structures, as they are used frequently in most construction projects (Kim et al., 2016).

During construction, “failure” of a temporary structure refers to a system that was unable to support the loads as specified by the design and construction requirements at the time of failure (Hadipriono et al., 1986; Rens et al., 2000). Collapse is one of the failure modes that could occur in temporary structures, where all or a substantial portion of a structure fails (Hadipriono et al., 1986). For typical temporary structures, such as formwork systems, the structures can suddenly collapse without any apparent warning (Moon et al., 2018). Such failures often contribute to serious injuries and loss of lives (Pisheh et al., 2010). Table 1.2 provides a list of some recorded failures of temporary structures and their consequences. The sources of the recorded failures include books, journal articles, and public databases including the reports from the Fatality Assessment and Control Evaluation (FACE) Program maintained by the National Institute for Occupational Safety and Health (NIOSH) (2020).

Table 1.2. Failures Due to Temporary Structures

Type of Failed Temporary Structure	Location and Year	Consequence	Reference
Formwork	US, 1971	Four workers lost their lives due to the failure of a 17-story concrete high-rise building in Boston, MA.	Feld and Carper (1997); King and Delatte (2004)
Formwork	US, 1973	14 construction workers were killed and 34 others were injured due to the collapse of the Skyline Plaza project in Virginia.	Feld and Carper (1997)
Formwork	US, 1981	11 workers were killed and more than 23 were injured because of the collapse of the five-story Harbour Cay condominium in Cocoa Beach, FL.	ACI (2014a)
Formwork	US, 1982	13 construction workers died because of the collapse of the temporary structure supporting the Riley Road Interchange Freeway Ramp in East Chicago, IN.	Feld and Carper (1997)
Formwork	US, 1998	During formwork removal, a worker fell off the formwork to the ground, and died from crush injuries when the form fell on him.	NIOSH (2015a)
Scaffolding	US, 1988	Two workers died after falling 48 feet to the ground level as the scaffold they were working on collapsed.	NIOSH (2015b)
Scaffolding	US, 2003	A collapse at a bridge construction project caused one fatality and three injuries.	El-Safty et al. (2008)
Formwork	Iran, 2006	The collapse resulted in the death of three, and injuries to seven, construction workers and a one-month project delay.	Pisheh et al. (2010)
Formwork	China, during 2005 - 2009	27 cases of serious collapses of formwork occurred. Approximately 100 workers lost their lives and more workers were injured.	Xie and Wang (2009)
Formwork	US, 2010	A worker lost his life because he stepped from a section of plywood formwork from which the vertical shoring had been removed, and fell 25 feet to the floor below.	NIOSH (2015c)
Formwork	US, 2013	Two workers were killed when formwork collapsed during concrete placement at a construction site in New York State.	NIOSH (2017)

To prevent injuries and fatalities due to failures of temporary structures, a number of researchers examined and evaluated the causes of temporary structure failures. Hadipriono and Wang (1986) stated that the causes of failures can be categorized into three types: triggering, enabling, and procedural causes. Triggering causes are defined as external events that initiate failures. Enabling causes are events that contribute to the deficiencies in the design and construction phases. Lastly, procedural causes are often hidden events that produce enabling and triggering events (Hadipriono and Wang, 1986). Based on the classification and a number of previous related research studies, a list of some of the leading causes of temporary structure failures, focusing on failures related to formwork, is summarized in Table 1.3. It is evident that the failures are mainly due to human negligence. If adequate considerations are given to temporary structures during the design and construction phases, and effective communication is ensured among stakeholders, the failures could have been prevented (Hadipriono and Wang, 1986; Bennett, 2004; Sheehan and Corley, 2013) and tragedies in which workers were injured or lost their lives due to failures of temporary structures would not have occurred.

Table 1.3. Common Causes of Formwork Failures

Type of Causes	**Details**	**Reference**
Triggering events	Strong wind	Hadipriono and Wang (1986), Rens et al. (2000), André et al. (2012)
	Heavy rain	Hadipriono and Wang (1986), André et al. (2012)
	Concentrated load	Hadipriono and Wang (1986), André et al. (2012)
	Improper removal of temporary components	Lew (1984), Hadipriono and Wang (1986), Feld and Carper (1997), ACI (2014a)
	Vibration and impact	Hadipriono and Wang (1986), ACI (2014a)

Table 1.3. Common Causes of Formwork Failures (Continued)

Type of Causes	Details	Reference
Enabling causes	Design errors	Lew (1984), Feld and Carper (1997), Haduong et al. (2018)
	Improper placement of temporary components	Hadipriono and Wang (1986), Xie and Wang (2009), Haduong et al. (2018)
	Inadequate components (e.g., diagonal bracings)	Hadipriono and Wang (1986), Feld and Carper (1997), Rens et al. (2000), André et al. (2012), ACI (2014a)
	Defective components (due to reuse)	Barbosa et al. (2014)
	Insufficient foundation strength and uneven foundation	Hadipriono and Wang (1986), André et al. (2012), ACI (2014a)
Procedural causes	Inadequate review of design	Hadipriono and Wang (1986), Bennett (2004), André et al. (2012), Sheehan and Corley (2013), Haduong et al. (2018)
	Inadequate review of construction (e.g., inspection and monitoring)	Lew (1984), Hadipriono and Wang (1986), André et al. (2012), Sheehan and Corley (2013), ACI (2014a)
	Insufficient training	Lew (1984), Feld and Carper (1997), Haduong et al. (2018)
	Lack of communication among stakeholders	Lew (1984), Hadipriono and Wang (1986), Sheehan and Corley (2013)

1.1.3 Approaches to Improving Performance of Temporary Structures

1.1.3.1 Traditional Approaches (without technology)

Given the fact that temporary structures are one of the most important and commonly used components in the industry, and the high injury and fatality rates due to temporary structure failures, conventional means to tackle the identified leading causes (Table 1.3) are explored in two different phases, the planning/design of the temporary structure phase and the construction of the temporary structure phase.

1.1.3.1.1 During the Planning/Design Phase

Considerable effort has been made in the past to assist in designing temporary structures and to incorporate safety considerations within designs. Different professional associations have published guidelines, standards, and specifications on the design of temporary structures. “Design Loads on Structures during Construction” (ASCE, 2015), “Formwork for Concrete” (ACI, 2014a) and “Building Code Requirements for Structural Concrete” (ACI, 2011) are a few examples of temporary structures design resources. Additionally, many subparts in the OSHA regulations for construction (29 CFR 1926) provide standards that are applicable to various types of temporary structures in the planning/design phase, such as Subpart L – Scaffolds and Subpart Q – Concrete and masonry construction. According to OSHA, temporary structures including scaffolds and concrete formwork shall be designed by a qualified person. Temporary structures that are used on small projects such as minor home renovations and for constructing short concrete walls and foundations may not be designed by a qualified person using formal engineering analysis and design principles. In such cases the temporary structures may be constructed simply by using field experience gained from prior projects. However, temporary structures that are used for large projects such as multi-story buildings, and unique temporary structures such as bridge falsework and shoring, are typically designed by qualified persons using standard engineering analysis and design techniques.

Research has also been carried out to learn from past temporary structure failures and to identify possible improvements in designs (Lew, 1984; Rens et al., 2000; Ratay, 2012; Sheehan and Corley, 2013; Pomares et al., 2014; Beale and André, 2017). A number of educational opportunities are offered from multiple resources to increase designers’ safety awareness of temporary structures. For example, the New York City (NYC) Department of Buildings provided training for designers with respect to the changes to the 2014 NYC Building Code that dealt with the design of temporary structures (Eschenasy and Spivack, 2014). As for potential designers, the need to include a tempoary structures class as one of the required parts of the curriculum for civil engineering programs has been identified (Okere and Souder, 2018). A number of universities, such as Oregon State University, University of Washington, University of New Mexico, and University of Florida, now offer classes to civil engineering students to teach them how to design temporary structures.

1.1.3.1.2 During the Construction Phase

Some of the approaches mentioned above which attempt to improve the design quality of temporary structures also provide guidance that can be implemented in the construction phase. For instance, in OSHA 29 CFR 1926.703(b)(8)(i), in addition to the design requirement related to shoring that is used for cast-in-place concrete projects, the standard mentions that after shoring is placed on site, the shores shall be inspected by an engineer qualified in structural engineering. For typical temporary structures, OSHA also requires a competent person to inspect and observe the construction site and operations. Similarly, ACI 381-11 (ACI, 2011) provides additional requirements for activities that take place during the construction phase when constructing structural concrete, such as the removal of forms, shores, and reshoring. Apart from the guidance and regulations provided by various professional organizations, lessons learned from the past temporary structure failures also point out poor field practices and the trajectories of improvements (Lew, 1984; Rens et al., 2000; Sheehan and Corley, 2013; Beale and André, 2017).

Based on the safety regulations and guidance, and the lessons learned from serious failures of temporary structures, a number of safety training programs have been developed to increase workers' safety awareness of potential hazards, and to provide the workers with information regarding safe operations when working with temporary structures. One example is the scaffolding eTool provided by OSHA (2017), which includes a safety checklist to assist workers in identifying hazards and potential controls that help prevent those hazards from occurring. For scaffolding, OSHA has also published detailed guidance and requirements for the use of scaffolds including details for the design, erection, dismantling, and inspection tasks (OSHA, 2002). Moreover, safety training programs, such as OSHA 10- and 30-hour construction training, provide education opportunities for activities related to temporary structures

(Cho et al., 2018). Some industrial organizations also provide industry safety practices in terms of references or guidance to industry practitioners (Yuan et al., 2016). Nevertheless, deficiencies exist in the current planning/design and construction phases of temporary structures. The temporary structures design process requires tedious effort (Singh et al., 2017), which consists of rigorous structural analysis. Because there is no standard and formal practice to generate temporary structure plans in the industry, the planning process is often performed manually and based on the planner's own experience (Kim and Fischer, 2007; Zhang et al., 2011).

Meanwhile, current practices regarding inspection and monitoring temporary structures mainly rely on manual inspections and observations by competent inspectors periodically to confirm whether the structures and the operations are in accordance with construction plans and governing regulations (Feng and Dai, 2014; Beale and André, 2017). Inspection results are based on visual assessments made by the inspectors (Cheng et al., 2009; Jung, 2014), or based on measurements through instrument-based surveying (Hope and Chuaqui, 2007; Moon et al., 2011; Feng et al., 2015b). The procedures that are currently used during the planning/design phase and the construction phase involving human effort are costly, time-consuming, and prone to human error (Kim and Fischer, 2007; Xie and Wang, 2009; Hwang and Liu, 2010; Zhang et al., 2011; Jung, 2014). Therefore, exploring and developing ways of adopting construction technologies to automate the design and planning process with safety considerations, and to improve the current practices in controlling and monitoring temporary structures, is warranted.

1.1.3.2 Approaches with the Use of Technology

Besides the conventional approaches, with the development of technological innovations, a number of researchers have explored ways to improve the design and control quality of temporary structures through the application of advanced technologies.

1.1.3.2.1 During the Planning/Design Phase

Before BIM was widely accepted and used in the industry, CAD models played important roles in providing stakeholders platforms to visualize construction information and to assist in planning projects. Jongeling et al. (2008) investigated the use of 4D CAD models in analyzing workflow and planning of temporary structures in order to select a feasible temporary structure plan based on space usage, distances between activities, productivity, and production costs.

As for BIM, it not only offers an innovative platform to construct accurate and precise 3D BIM models, but also is a process for different stakeholders to work together (Azhar, 2011). Using a BIM model as a construction aid, VDC tools provide more functions to facilitate the planning and design processes, such as constructability reviews (Luth, 2011). While the use of VDC is primarily focused on permanent structures, a small number of researchers have examined the applications of VDC to many types of temporary structures. For example, research studies have been conducted on the topics of scaffolding design and planning (Kim and Teizer, 2014; Kim et al., 2016; Kim et al., 2018b), formwork constructability assessment (Kannan and Santhi, 2013), and formwork design and planning (Singh et al., 2016; Singh et al., 2017; Jin and Gambatese, 2019).

1.1.3.2.2 During the Construction Phase

Meanwhile, to enhance the inspection and monitoring quality of temporary structures on sites, a number of research studies have been carried out to test and examine the feasibility of a variety of technologies. A series of studies performed by Moon et al. (2011; 2015; 2017) proposed to use a local wireless network, named Ubiquitous Sensor Network (USN), for real-time data acquisition in monitoring the performance of formwork during concrete pouring, with the integration of web applications, smart glass applications, and mobile devices. Additionally, another series of research studies by Yuan et al. (2014; 2015; 2016) focused on scaffolding, and proposed to use a Cyber-Physical System (CPS) to link the virtual model of a temporary structure with the physical structure of the temporary structure on site for the purpose of real-time monitoring.

The application of RFID on temporary structures has also been examined. For instance, Yabuki and Oyama (2007) proposed to use passive RFID to facilitate the asset management of temporary structure components on site. Additionally, in a study performed by Atherinis et al. (2018), RFID technology was used to check if temporary structure members were placed on site and, in combination with a virtual 3D model, both the presence and position could be confirmed. The results showed the proposed smart system achieved a more accurate and efficient result than experienced using the traditional approach.

Other studies, such as those conducted by Jung (2014), Feng and Dai (2014), Feng et al. (2015b) and Jung et al. (2019), attempted to use images or videos, through image processing algorithms, to detect possible temporary structure failures. Although the function of real-time monitoring of temporary structures using images/videos is still at the conceptual and preliminary stages as the focus area of these studies remains on the domain of comparing and selecting appropriate edge detection and image matching techniques, the attempts showed the possibilities of using images or videos to assess structural stability of temporary structures when they are in use.

1.2 Motivation

Temporary structures play significant roles in the quality, productivity, cost, and safety of all construction projects (Ratay, 2004). Minimal research has attempted to improve the safety performance of temporary structures, even though temporary structures are often associated with high accident rates and severe consequences. Furthermore, temporary structures have not benefited much from technological improvements.

The innovation-development process typically begins with identifying a problem or need to stimulate research and development activities to solve the problem or need (Rogers, 2003). Therefore, it is important to investigate the current practices that are used to design, inspect, and monitor temporary structures in order to find the deficiencies and to confirm the need for improvement. Then, to adopt an innovation, the first phase is initiation (Zaltman et al., 1973). Some key activities of this stage include investigating knowledge of an innovation and attitudes toward the innovation. Mitropoulos and Tatum (1999) and Blayse and Manley (2004) also highlighted the importance of understanding the attitudes of decision-makers and individuals who are involved in the process towards an innovation. Moreover, the construction industry has been identified to be conservative in its adoption of emerging technologies (Andresen et al., 2002; Ahn et al., 2019; Jung et al., 2019). Industry practitioners who have worked in a certain way in the industry for decades are often reluctant to adopt new technologies in their practices (Nnaji et al., 2018a; Muzafar, 2019).

Despite previous efforts that have shown promising results in improving the performance of temporary structures during the design and construction phases, none of the previous research studies investigated the above-mentioned problems and key technology selection factors. It is necessary to investigate professionals' attitudes with respect to applying technologies on temporary structures, to facilitate the technology adoption, implementation, and diffusion process.

1.3 Research Goal and Plan

To fulfill the abovementioned knowledge gaps, the overarching goal of this dissertation is to advance the body of knowledge and make practical contributions to the integration of temporary structures with advanced technologies. This goal is met through the identification of the desires and needs associated with adopting technologies for temporary structures, and the development of tools to improve the quality of temporary structures in the design and construction phases of a construction project.

The specific research questions that the present study attempts to answer are:

1) What are the current methods used in the design, inspection, and monitoring processes of temporary structures with respect to the level of attention received

compared to that of permanent structures? Where are the needed areas of improvement?

2) What are design and construction professionals' perspectives on adopting innovative technologies in support of designing and monitoring temporary structures?
3) To improve design quality, what features need to be included in the design tool? How can the features be incorporated in the design tool?
4) What technologies have been used to monitor the structural health of permanent structures? What are the technology selection criteria that are applicable to select an appropriate technology for temporary structure control and monitoring? What is the relative importance of the identified technology selection criteria? Can the technologies also be used for temporary structures?
5) To improve onsite inspection and monitoring quality, what method can be used to support decision-making when selecting an appropriate technology given that there are a variety of options? Can the selected technology be useful in monitoring performance?

To attain the overall goal and answer the research questions, the research study is designed to follow the research flow shown in Figure 1.2. The dissertation consists of three manuscripts. The first manuscript (Manuscript #1) focuses on investigating the current practices of the design and inspection methods for temporary structures, as well as determining the improvements that could be made to improve the design and monitoring quality. Manuscript #1 also identifies design and construction professionals' desires to adopt advanced technologies. Manuscript #1 is designed to answer research questions #1 and #2, and the former parts of research questions #3 and #4.

For Manuscript #2 and Manuscript #3, the type of temporary structure focused on is concrete formwork system. Based on the suggested tool and improvements identified from the results of Manuscript #1, the second manuscript (Manuscript #2) aims to develop a BIM plug-in to achieve automation in designing and modeling temporary structures with safety and health considerations. Manuscript #2 aims to answer the latter part of research question #3. Lastly, the goal of the third manuscript (Manuscript #3) is to select an appropriate technology based on specified selection criteria and their importance identified in Manuscript #1, and to develop a monitoring tool based on the selection result. Manuscript #3 attempts to answer research questions #5 and address research question #4. The specific research objectives of all the manuscripts are also shown in Figure 1.2. The expected research outcomes are the needs and desires to use advanced technologies in temporary structures as well as tools to improve the design, inspection and monitoring performance of temporary structures.

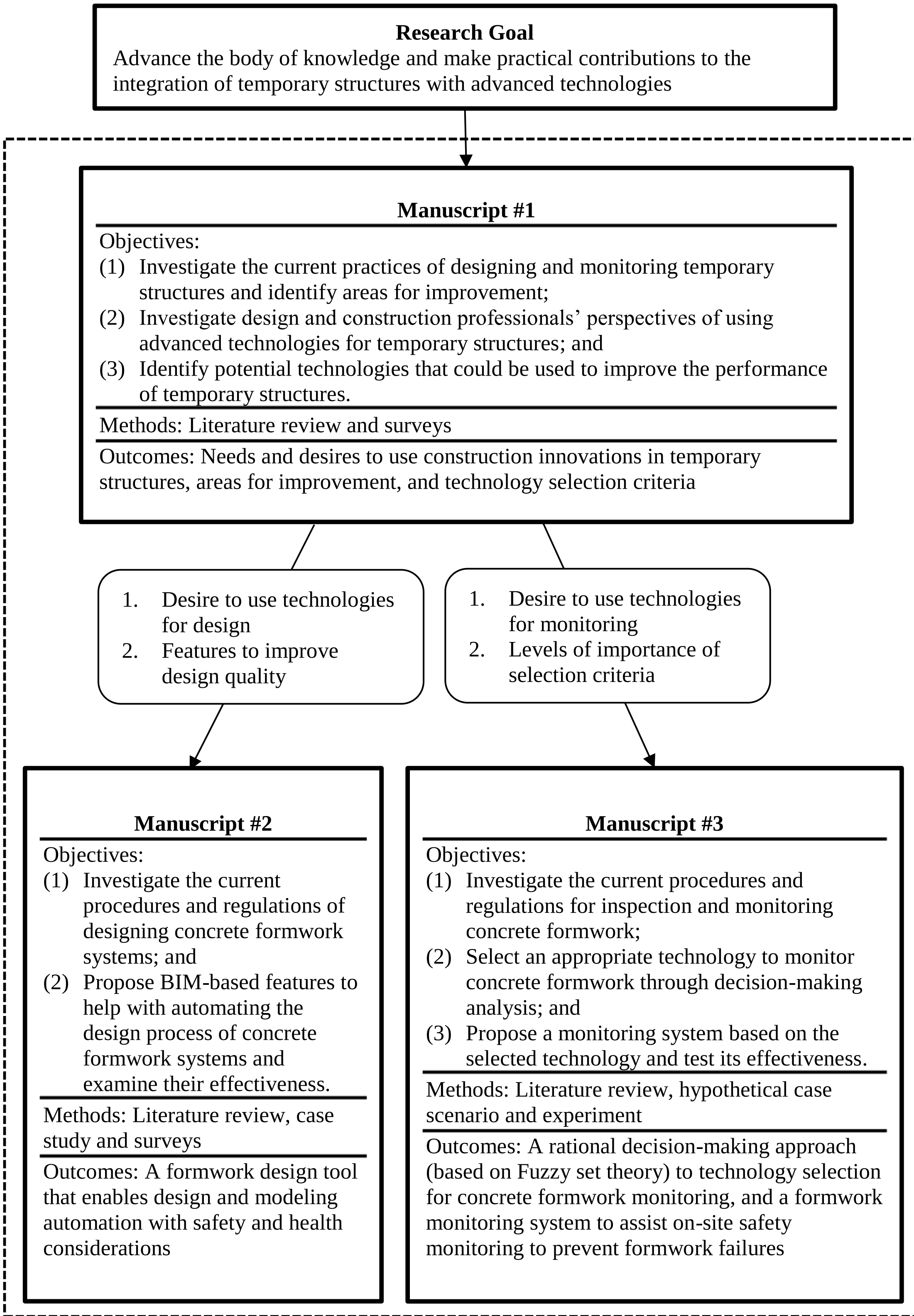

Figure 1.2. Research Flow

1.4 Outline of Dissertation

This dissertation consists of five chapters, and presents the three abovementioned manuscripts (Chapters 2 – 4). A summary of each chapter is provided below.

Chapter 1 provides an overview of and introduction to the research study, which includes background information of the present study, the research goal and plan, as well as an outline of the dissertation. In addition, Chapter 1 presents a literature review of relevant research topics including construction safety, technology applications for construction safety, temporary structures and their failures, and (non-technological and technological) approaches to improving the performance of temporary structures.

Chapter 2, titled "Exploring the Potential of Technological Innovations for Temporary Structures: A Survey Study," is an exploratory study that investigates design and construction professionals' views regarding adopting technologies for temporary structures. The contents of the chapter are an adapted version of the work published in the *Journal of Construction Engineering and Management*, American Society of Civil Engineers (ASCE), in June 2020. The contents of this chapter is also referred to as "Manuscript #1" in this document.

Chapter 3, titled "BIM for Temporary Structures: A BIM API for Concrete Formwork," proposes a BIM-based tool to assist formwork design and modeling. A portion of the contents of the chapter were published in the *Proceedings of the Canadian Society for Civil Engineering (CSCE) Annual Conference*, Laval (Great Montreal), Canada, 12-15 June 2019. Part of the work will also be submitted for publication in a scholarly archival journal. Chapter 3 represents "Manuscript #2."

Chapter 4, titled "Selection and Application of Technologies for Monitoring Formwork during Concrete Placement," proposes to use a fuzzy multi-criteria decision approach to select appropriate technology to monitor concrete formwork performance, and presents the development of a monitoring tool based on the selection result. The content related to technology selection in Chapter 4 was published in the *Proceedings of the*

ASCE Construction Research Congress (CRC), Tempe, 8-10 March, 2020. The content related to the developed monitoring tool is expected to lead to a scholarly archival journal. The content of this chapter is referred to as “Manuscript #3.”

Finally, Chapter 5 presents the main conclusions of the entire study, a description of how each of the research objectives was met, study limitations, as well as recommendations for future research and implications.

1.5 Terminology

To avoid ambiguity and improve the readability of the present work, this section presents a list of terms and concepts used in this dissertation.

- **Application programming interface (API)**: an interface that enables interactions between multiple applications (Oti et al., 2016). The BIM-API in the dissertation refers to the BIM plug-in. Since the BIM authoring tool used in the present work is Revit, BIM-API also refers to the Revit plug-in in the present work.

- **Augmented reality (AR)**: a technology that integrates three-dimensional (3D) virtual objects into a 3D real environment, which complement and enrich of the real world (Webster et al., 1996; Azuma, 1997).

- **Building information modeling (BIM)**: not only a software program, but also a process that involves integrating all design and construction elements into a virtual model that all project stakeholders can access and work on (Azhar, 2011).

- **Computer-aided design (CAD)**: the use of computer technology to aid the design of a part, product or project (Aouad et al., 2013).

- **Concrete formwork**: molds used for concrete construction to support permanent concrete forming and curing until the structure gains sufficient strength to support itself, as well as to support construction live load (ACI, 2014a).

- **Deflection**: the movement of a structure or structural member when subjected to a load (Collinsdictionary.com, 2021).

- **Displacement**: the difference between the initial position and any later position of something (Merriam-Webster.com, 2021).

- **Flex sensor**: a type of sensor that measures the amount of deflection or bending.

- **Inertial measurement unit (IMU)**: an electronic device that measures velocity, orientation, and/or gravitational force (Ahmad et al., 2013).

- **Internet of things (IoT)**: a system that connects physical objects together to gather information via the Internet (Ashton, 2009; Xia et al., 2012).

- **Light detection and ranging (lidar)**: a remote sensing approach that measures ranges using laser pulses (Reutebuch et al., 2005).

- **Geographical information system (GIS)**: a system that captures, stores, manages, analyzes and displays spatial and geographic data (Krichen et al., 2013).

- **Global positioning system (GPS)**: a satellite-based system that provides positioning, navigation, timing and velocity information data to users (U.S. Air Force, 2015).

- **Radio frequency identification (RFID)**: the use of an object attached to a product, animal, or person for identification and tracking purposes using radio waves (McAdams, 2011).

- **Temporary structures**: 1) systems and assemblies used to temporarily support permanent work (e.g., formwork, cofferdams, earthwork sheeting, shoring, etc.); 2) systems and assemblies that serve as platforms for construction workers (e.g., scaffolding, ramps) during construction; and 3) structures built for a temporary purpose (e.g., temporary tent, temporary entertainment structure, etc.) (Jung, 2014; Yuan et al., 2016). The primary type of temporary structure focused on in the present work is concrete formwork.

- **Ultra-wideband (UWB)**: a technology that is able to transmit data wirelessly in low-power and short- to medium-range conditions (Sahinoglu et al., 2008).

- **Unmanned aerial vehicle (UAV)**: an aircraft capable of flying in the air with no person on board (Eisenbeiss, 2004).

- **Ultrasonic sensor**: an electronic device that measures the distance to an object using ultrasonic sound waves (MaxBotix, 2020).

- **Virtual reality (VR)**: a technology that provides the user a simulated environment for an immersive and responsive virtual world experience (Brooks, 1999; Sacks et al., 2013).

- **Virtual design and construction (VDC)**: the approach to integrate multi-disciplinary performance digital models to visualize and plan construction projects, such as designs, budget, schedules, and safety, and to facilitate the communications among the architects, engineers, contractors, subcontractors and owner (Kunz and Fischer, 2012; Autodesk, 2021c).

- **Wearable sensing technology**: a set of different sensing systems that can be attached to humans as accessories, or embedded in clothing, to acquire physiological, environmental and location information (Awolusi et al., 2018; Ahn et al., 2019).

- **Wireless sensor network (WSN)**: a system that integrates a number of sensor nodes working together to monitor the condition of a pre-defined region (Yick et al., 2008).

2. MANUSCRIPT #1 – EXPLORING THE POTENTIAL OF TECHNOLOGICAL INNOVATIONS FOR TEMPORARY STRUCTURES: A SURVEY STUDY

The content of Chapter 2 is an adapted version of the following journal article.

Jin, Z. & Gambatese, J. 2020. Exploring the Potential of Technological Innovations for Temporary Structures: A Survey Study. *Journal of Construction Engineering and Management*, 146, 04020049.

2.1 Abstract

Technology innovations, such as VDC tools, lidar, GPS, and other vision-based or sensor-based systems, provide approaches that designers, builders, and other stakeholders can adopt to address, manage, and tackle design, planning, and site safety issues effectively during the design and construction phases. Nevertheless, the majority of technology applications have focused on permanent structures rather than temporary structures such as concrete formwork and scaffolding. Due to the "temporary" nature of temporary structures, stakeholders might easily underestimate their importance and pay less attention to their safety, quality and performance. Therefore, the benefits received for temporary structures as a result of the development of advanced technologies have been limited. This manuscript aims to investigate, through a survey questionnaire, the current practices related to the level of attention given to temporary structures compared to that of permanent structures, and professionals' viewpoints of using construction innovations on temporary structures. Based on empirical evidence from professionals who have experience with either designing or constructing temporary structures, the findings reveal that the industry currently pays less attention to temporary structures, and more attention is anticipated to improve safety performance related to temporary structures. In general, design and construction professionals hold positive attitudes toward applying construction innovations on temporary structures to improve the design quality and structural health when they are in use.

2.2 Introduction

Technological improvements in construction provide new means for professionals to improve design quality and construction performance in terms of productivity, quality, and safety. Prior to construction, VDC which utilizes a 3D BIM model to facilitate the planning and design processes (Luth, 2011), provide a means for designers and contractors to work together through an integrated and collaborative environment. Thus, site safety concerns could be addressed using VDC tools with the possibility of eliminating or reducing the hazards before they are present on the site (Jin et al., 2018). Likewise, through an integrated process, communication among stakeholders is improved so that site planning can be performed efficiently and effectively through visualization and simulation.

Meanwhile, the uses of innovative construction technologies during the construction phase are also showing encouraging results. For example, utilizing the rapid and reliable spatial data acquisition offered by lidar, researchers have examined a wide range of applications during the construction process, such as monitoring the performance of earthmoving operations for roadway projects (Navon and Shpatnitsky, 2005), assessing concrete slab flatness (Puri et al., 2018), and conducting progress monitoring for building projects (Turkan et al., 2012; Bosché et al., 2015). Moreover, to assess the structural health of permanent structures, lidar is one of the means that could be used to assess structural damage (Olsen et al., 2010), and to measure structural displacement (Park et al., 2007). Other technologies that have been applied to structural health monitoring for high-rise buildings, bridges, and other structures include GPS (Ni et al., 2009; Yi et al., 2013), vision-based systems (Lee and Shinozuka, 2006; Park et al., 2010), and sensor-based systems (Lynch and Loh, 2006; Ye et al., 2014).

Technological improvements in construction have been beneficial to permanent structures, but compared to permanent structures, the benefits received for temporary structures are so far quite limited. Nevertheless, temporary structures are considered as one of the most extensively used components for construction projects (Beale and André, 2017). Nearly three-fourths of the construction workers in the US perform construction activities on temporary structures or near temporary structures (Yuan et al., 2016). Temporary structures, such as concrete formworks, are also critical and essential to ensure the success of projects (ACI, 2014a; Jin and Gambatese, 2019). More importantly, temporary structures are one of the common types of structural elements that fail in construction (Eldukair and Ayyub, 1991; Wardhana and Hadipriono, 2003; Buitrago et al., 2018). Temporary structures have contributed to injuries and fatalities in the industry (Ismail and Ab Ghani, 2012), as shown in the failure investigation studies conducted by Cattledge et al. (1996), Yates and Lockley (2002), and Haduong et al. (2018).

Even though the role of temporary structures in the cost, productivity, safety, quality, and aesthetics of construction projects has increased in a consistent fashion over time (International Federation for Structural Concrete (fib), 2009), compared to the number of studies that have focused on permanent works, limited research efforts have been made to select and to apply appropriate technologies to temporary structures. Given the fact that technologies have been successfully applied to permanent works, the use of advanced technologies might be beneficial to temporary structures as well.

Thus, the present study aims to investigate the current practices of temporary structures during the design and construction phases, to explore the potential of applying technological innovations for temporary structures, and to gain professionals' perspectives about the application. To achieve this goal, a survey was conducted in which a questionnaire was distributed to design and construction professionals through a mixed-method sampling technique. The findings of the present study are expected to reinforce the important role of temporary structures in the industry and contribute to the body of knowledge by providing professionals' insights in terms of room for improvement of temporary structures during the design and construction phases, technology selection criteria as well as their relative importance, and viewpoints regarding adopting construction technologies for temporary structures.

2.3 Background

2.3.1 Temporary Structures and Their Failures[1]

2.3.2 Approaches to Improving Performance of Temporary Structures[2]

2.4 Point of Departure and Research Questions

Temporary structures play significant roles in the construction industry and considerable past endeavors have been made to improve their safety performance. However, temporary structures are still associated with high accident rates and severe consequences. Apparently, the current planning/design and construction phases of temporary structures still have deficiencies related to the cost, time, and accuracy of the temporary structure design, planning, construction and use, as described previously. In many cases, design, implementation and inspection of temporary structures are performed using manual processes that can be time-consuming, tedious, and error-prone. Exploring new ways to perform such tasks, and as a result, save time and cost and prevent errors that lead to injuries, is desirable. Adopting technology innovations for temporary structures might be a potential solution for achieving such improvement.

As stated in Section 1.2, it is necessity to investigate the issues with the current practices that are used to design, inspect, and monitor temporary structures and professionals' attitudes with respect to applying technologies on temporary structures, in order to facilitate the technology adoption, implementation and diffusion processes.

The identification of the needs and desires of using modern technologies in temporary structures, and the development of features, such as automating the design process with safety considerations and enabling real-time monitoring operations during the construction phase, would serve as invaluable contributions to bridge the knowledge gap identified above.

Based on the literature review and identified knowledge gaps, the research aims to answer the following research questions:

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[1] Please refer to Section 1.1.2 for the literature review of this part.
[2] Please refer to Section 1.1.3 for the literature review of this part.

1) What are the current methods used in the design, inspection, and monitoring processes of temporary structures with respect to the level of attention received compared to that of permanent structures? Where are the needed areas of improvement?
2) What technologies have been used to design permanent/temporary structures, or to monitor the structural health of permanent/temporary structures? What are the technology selection criteria that are applicable to select an appropriate technology for temporary structure control and monitoring? What is the relative importance of the identified technology selection criteria?
3) What are design and construction professionals' perspectives on adopting innovative technologies in support of designing and monitoring temporary structures?

2.5 Research Method

The data collection method used in the present study is a survey. One major reason behind the use of a survey is that no empirical data regarding technology usage for temporary structures are available. Another reason is that conducting survey is one of the most cost effective ways to obtain opinions from a large number of diverse professionals who are distributed across different geographical locations (Fernandez-Solis et al., 2013; Karakhan and Gambatese, 2017).

2.5.1 Survey Design

A survey questionnaire was developed in *Qualtrics*. The survey questionnaire was initially designed to be used for Manuscript #1 to solicit professionals' opinions on the application of technologies to temporary structures (Part 1 in the survey). After the formwork design and modeling tool (the focus of Manuscript #2) was completed, the survey was then extended to include several questions to verify the workability and effectiveness of the developed tool (Part 2 in the survey). A copy of the questionnaire (both Part 1 and Part 2) is available in Appendix I. Please note that the survey questions mentioned in this manuscript are only related to Part 1 in the survey.

The survey questionnaire was developed based on a review of past research on temporary structures and construction technologies in the design and construction phases. All of the survey components were intended to provide data from which conclusions about how to improve the performance of temporary structures could be derived.

To provide a thorough investigation of technologies that could apply to temporary structures and professionals' views of the applications, potential technologies that could be used to improve the performance of temporary structures in the design and construction phases were initially identified (Table 2.1). The technologies include those that have been applied to design permanent structures, perform permanent structure health monitoring in terms of assessing structural displacements, or used in previous temporary structures related research.

For controlling and monitoring the performance of temporary structures, a set of technology selection criteria was pre-determined based on studies that were conducted with respect to construction technology selection (Jiang et al., 2012; Ibadov and Rosłon, 2015; Nnaji et al., 2018b), technology applications for structural health monitoring (Lynch, 2006; Park et al., 2007; Feng et al., 2015b), and technology assessment (Kopsida et al., 2015). As a result, ten criteria were determined which can be categorized into four aspects: performance, interference, cost, and practicability. The details of the identified selection criteria are present in Table 2.2.

The survey questionnaire consisted of four main sections. The first part solicited background information on the respondents in terms of the type(s) of temporary structures that they are familiar with, years of work experience, type of company in which they are employed, job title, etc. The second part of the questionnaire consisted of questions related to the current temporary structures design and inspection practices. The objectives of this part are to identify if the industry currently pays equal attention to temporary structures compared to permanent structures during the design and construction phases, and if more attention should be given to temporary structures.

Additionally, the leading causes of temporary structures failures are also expected to be identified from the professionals' viewpoints. Moreover, the respondents were asked to assess current inspection performance with respect to frequency, accuracy, cost, time, etc.

Table 2.1. Identified Potential Construction Technologies to Improve the Performance of Temporary Structures

Ideal Function	Identified Technology		Reference
Improve design quality and incorporate design for safety for temporary structures	VDC includes BIM		Meadati et al., (2011), Kannan and Santhi, (2013), Kim and Fischer (2014), Kim et al. (2016; 2018), Singh et al., (2016; 2017)
Control and monitor performance of temporary structures	Sensor-based technologies	Radio-frequency identification (RFID)	Yabuki and Oyama (2007), Ikemoto et al. (2009), Atherinis et al. (2018)
		Global Positioning System (GPS)	Im et al. (2011), Yi et al. (2013)
		Other sensor-based technology (sensor networks, wireless sensors, etc.)	Li et al. (2004), Lynch and Loh (2006), Moon et al. (2011; 2015; 2017), Yuan et al. (2014; 2015; 2016)
	Vision-based technologies	Video/photo logs	Jung (2014), Feng and Dai (2014), and Feng et al. (2015), Jung et al. (2019)
		Laser scanning	Park et al. (2007), Yang et al. (2016)
		With the integration of drones (unmanned aerial vehicles (UAVs))	Ellenberg et al. (2014), Reagan et al. (2017), Sony et al. (2019)

The third part of the questionnaire focused on identifying and assessing opportunities to improve the safety of temporary structures. In one of the questions, opinions from the participants were requested to select the features that they feel technologies could be helpful with when designing temporary structures, such as design deficiencies identification, safety hazard identification, and design modifications based on safety considerations, and effective communication with contractors and other stakeholders.

In addition, participants were invited to rate 10 technology selection criteria (Table 2.2) that should be considered when selecting technologies to control and monitor temporary structures on site in terms of their importance. The ratings were based on a scale of 1 to 5, where 1 indicates not at all important, and 5 means extremely important.

Table 2.2. Identified Technology Selection Criteria, Categories, and Definitions

Categories	Criteria		Definition
Performance	C1. Meets required needs; has required features		The ability to monitor the performance of temporary structures (e.g., measure structural displacement).
	C2. Provides desirable results (level of accuracy, robustness, etc.)		*Level of accuracy*: the degree to which the measurement is correct when compared to the ground truth. *Robustness*: the ability to return correct and useful outputs with missing/extreme data points.
	C3. Quality of data (reliability)		The degree to which the data is accurate, applicable to technology performance, and sufficient in amount without loss during transmission.
Interference	C4. Less disruption to operations		The extent of attachment and installation on the physical structures.
Cost	C5. Cost of initial purchase		The purchase cost at the beginning stage of construction.
	C6. Cost of installation and maintenance		The cost associated with device installation and settings, as well as the long-term maintenance cost of the device when in use.
Practicability	C7. Easy to use and implement		The ease with which typical construction personnel can operate the device.
	C8. Training requirements		The level of training users have to receive to operate the system.
	Time	C9. Time efficiency in data acquisition	The time and effort required to collect the required data to achieve a desirable result.
		C10. Time efficiency in data processing and interpretation	The time and effort required to conduct post-data processing after data collection, and to predict the performance result.

The last part of the survey was related to construction technology. This technology-related part consisted of two questions. One question aimed to investigate the current usage of the identified technologies (Table 2.1) on site in general (not specifically for temporary structures), and the other question attempted to find which identified technologies are promising for application to temporary structures from industry professionals' perspectives.

A variety of question types, such as multiple-choice, 5-point Likert scale, and open-ended questions, were included in the questionnaire. Therefore, quantitative data were captured using closed-ended questions and qualitative data were received via open-ended questions. The survey questionnaire was designed to be completed in 10 – 15 minutes. Participation was voluntary, and no compensation was offered. Participants could skip any questions that they were unwilling to answer. Before distributing the questionnaire to potential respondents, the survey was approved by the Institutional Review Board (IRB) of the authors' institution.

2.5.2 Sampling Method

The target population of the study was professionals who have worked with temporary structures and have a basic understanding of construction technology, which includes design professionals, general contractors, specialty contractors, suppliers, and scholars. However, it was difficult for the researchers to identify whether a potential respondent has worked with temporary structures or not, as the interest of the research is on a specific topic with a small group of professionals compared to those who have worked with permanent structures. A contact list of the designers, constructors, and suppliers who have worked with temporary structures is not readily available. Therefore, the survey was sent to a broad range of design and construction professionals to reach the potential target population by adopting a mix of sampling techniques.

The sampling method used for the present study is non-probability sampling, which is the opposite of probability sampling, where it is required that randomness be built into the sampling design to minimize selection bias (Mendenhall et al., 2006). Non-probability sampling does not involve random selection of participants; the selection mainly relies on the judgment of the researchers. Even though prior studies that adopted probability-based sampling reached beneficial results since the sampling method minimized the chance of bias within data due to its random selection process, it is difficult to collect data this way in construction research (Abowitz and Toole, 2009). Purposive/judgmental sampling, a form of non-probability sampling, is commonly used in construction research (Karakhan and Gambatese, 2017). The authors adopted purposeful/judgment sampling as the primary sampling technique for the present study: the sample was selected purposefully to form a group of professionals that are familiar with temporary structures and are interested in construction technology. On the other hand, snowball sampling (another non-probability sampling technique) is also common in construction research (Abowitz and Toole, 2009). Participants who finished the survey were encouraged to forward the survey invitation to other professionals who might also be interested in participation. The professionals contacted through sampling networks were viewed as being reached by snowball sampling. Such sampling techniques are appropriate and preferred when it is infeasible to reach sample elements at random and when the desired population requires rare characteristics (Salganik and Heckathorn, 2004).

2.5.3 Survey Questionnaire Distribution

The survey was initially distributed through contact lists that were collected from the publicly available websites of the Associated General Contractors (AGC), Associated Builders and Contractors (ABC), American Society of Concrete Contractors (ASCC), and Structural Engineers Association (SEA) in a few states. Members of the ACI Committee 347 and the ASCE Construction Institute Temporary Structures Committee were also reached. Moreover, the survey was also sent to scholars who have performed research studies related to temporary structures and construction technologies, along with professionals on the authors' contact lists. Some of the invited participants who completed the survey also forwarded the survey invitation to those who might also be interested in the study. The snowball sampling effect brought more potential respondents. Due to the mixture of sampling techniques used, the total number of surveys distributed is unknown.

It is worth mentioning that, the survey questions pertaining to professionals' views and attitudes towards the use of technologies on temporary structures (Part 1 of the survey) were distributed again when soliciting design professionals' views on the developed formwork design and modeling tool (Manuscript #2). However, to avoid issues resulting from duplicate participation, the responses to multiple-choice and Likert scale questions are not included in the research findings shown below. Only constructive feedback to the open-ended questions are included.

2.6 Survey Results and Analysis

Through the contact lists and referral networks, a total of 60 responses were received. As mentioned previously, since the survey invitation was distributed through emails and the internet, and included snowball sampling, the number of professionals who received the link is unknown; therefore, the response rate is not known as well. As suggested by Seo (2005), Goh and Chua (2016), and Toh et al. (2017), responses with a completion rate of 95% or above and without any indication of systematic response patterns were used in the subsequent data analysis. Fourteen (23%) of the responses were less than 95% complete or included indication of a systematic response pattern. As a result, 46 of the 60 responses (77%) were evaluated in the analysis.

2.6.1 Participants' Background Information

The participating professionals have extensive work experience in the AEC industry. Out of the 46 responses, 78% of the respondents have more than 10 years of work experiences in the industry. All of the participants indicated that they have worked with temporary structures. With respect to the type of company they work for, 43% work for general contractors or subcontractors, 35% for engineering firms (either structural, geotechnical, or construction engineering), 20% for suppliers, and 2% in academia. The survey generated nearly 35% of the responses from professionals in upper management roles, such as president, vice president, director of engineering, division/regional manager, etc. Therefore, the survey provided information from respondents who represent a wide spectrum of the professionals that work with temporary structures with diverse roles. As mentioned previously, when considering adopting construction innovations, investigating the attitudes of individuals who are involved in the process is essential.

Regarding the type of temporary structures that the respondents are familiar with, concrete formwork was selected by 91% of the participants, followed by shoring (83%), scaffolding (67%), and earth-retaining structures (50%). Other temporary structures mentioned in the responses included temporary bridges, cofferdams, tower crane foundations and connections, and other common types of temporary structures.

2.6.2 Current Practices of Temporary Structures

Generally speaking, regarding the current level of attention paid to temporary structures, the responding professionals indicated that less attention is paid to temporary structures than to permanent structures during the planning/design phase and the construction phase, as shown in Figure 2.1. In the planning/design phase, the majority of the respondents felt much less (65%) or less (26%) consideration is given. Participants held similar opinions during the construction phase as the majority of them agreed that either much less (24%) or slightly less (50%) attention is paid to temporary structures when compared with permanent structures. When inviting participants to express their agreement with the statement that more attention should be given to temporary structures either during the design and planning phase or the construction phase, Figure 2.2 shows that more than 85% of the responses strongly or somewhat agreed that more attention is necessary. Only a small portion of responses (4%) disagreed with the statement.

It is worth mentioning that as observed in Figure 2.1, participants were generally more unsatisfied with the designs or plans of temporary structures than the practices in the construction phase. The results, shown in Figure 2.2, are consistent with the finding; a slightly higher percentage of responses (4%) strongly/somewhat agreed with the statement that more attention should be given to temporary structures in the design/planning phase than in the construction phase. Both Figure 2.1 and Figure 2.2 highlight the necessity of giving more attention to temporary structures during the design and construction phases.

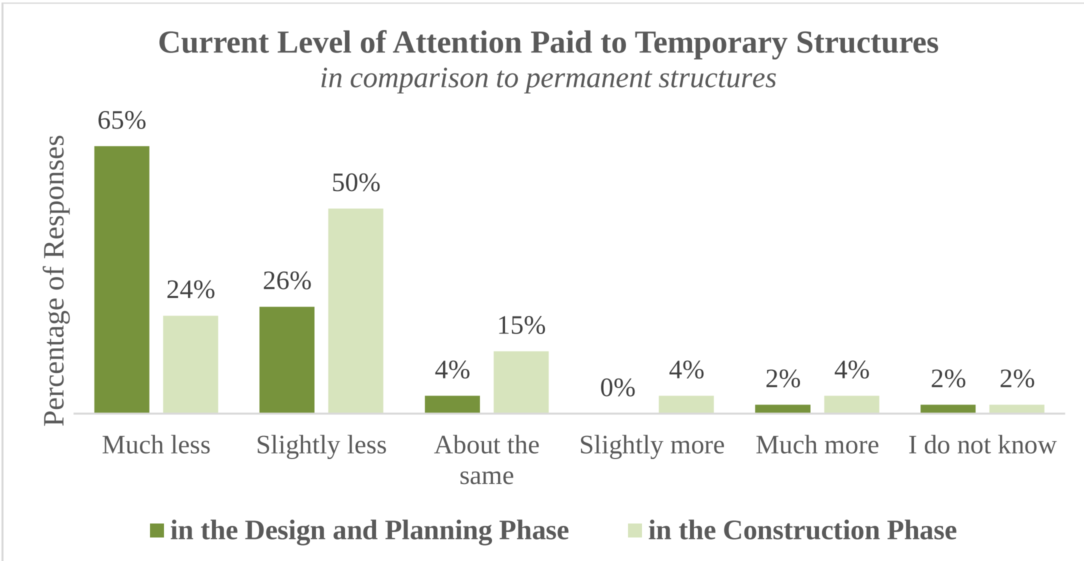


Figure 2.1. Viewpoints from Design and Construction Professionals on the Level of Attention Paid to Temporary Structures *(n = 46)*

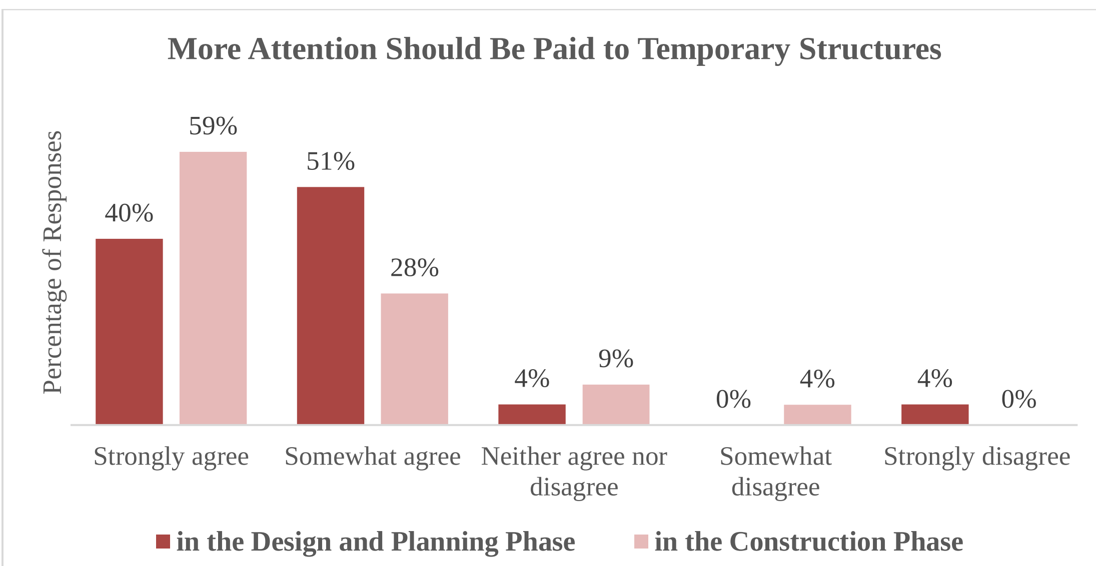


Figure 2.2. Agreement with the Statement That More Attention Should Be Given to Temporary Structures *(n = 46)*

With respect to the causes to temporary structure failures, the participants were invited to select all factors that may apply based on their experiences. Seven factors were preidentified by the authors based on literature review, which is summarized in Table 1.3: 1) design errors, 2) improper assembly/removal, 3) insufficient control and monitoring during operations, 4) lack of communications among the permanent structure's designer, general contractor, and subcontractor, 5) unstable foundation, 6) heavy construction loads (overloaded by materials, equipment, personnel), and 7) bad weather. Additionally, participants were given the chance to add any other contributing factors to the failures they observed. It turns out that the leading causes to temporary structure failures, according to the respondents, are: improper assembly/removal (83% of respondents), insufficient control and monitoring during operations (63%), design errors (39%), lack of communications (37%), heavy construction loads (20%), bad weather (17%), and unstable foundation (13%). Other factors identified by one or more of the participants include: no design provided or used, unqualified engineers performing the design, lack of temporary structure design review, lack of communication between the form designer and the field, field changes to the design without consultation and permission of the designer, poor planning and implementation (e.g, manufactured products used beyond their intention use), material deficiencies, and involved parties lack education and training.

The findings regarding causes of failure are in line with the work of Hadipriono and Wang (1986), in which an investigation of 85 major falsework collapses of bridges and buildings was conducted. Most failures occurred due to procedural causes (e.g., insufficient control and monitoring during operations, inadequate review of designs, lack of communications, lack of training and education, etc.), which also produce enabling events (e.g., improper assembly/removal, design errors, unstable foundation, etc.), and/or triggering events (e.g., heavy construction loads, bad weather etc.). Therefore, inadequacies in procedural methods, used in the design and construction phases, are identified as the root causes of temporary structure failures. Effective quality control measures should be taken to address inadequacies in procedural methods. Besides, proactive measures are also anticipated to be set in place to reduce the likelihood of enabling, triggering and procedural events occurring.

Furthermore, one of the research objectives is to investigate the current inspection quality of temporary structures. To assess the inspection quality, participants were asked to rate five measurement items using 5-point scales with regard to controlling and monitoring temporary structures during the construction phase. The results are presented in Table 2.3. It was found that the participants are generally unsatisfied with current inspection practices in terms of frequency, level of accuracy, and interruption to operations. In particular, frequency of inspection received the lowest average rating, which suggests that the number of inspections conducted to ensure temporary structures are constructed in conformance with the design and have sufficient structural stability is not adequate. Furthermore, the majority of the participants agreed that not enough time and cost is spent on inspections of temporary structures, with only a small portion of participants having a different opinion.

Table 2.3. Professionals' Ratings of Current Practices Regarding Inspections of Temporary Structures *(n = 46)*

Item	**Scale**	**Rating**			
		Average	**Standard Deviation**	**Minimum**	**Maximum**
Frequency of inspection	1 = extremely low, 3 = adequate, 5 = too many	2.05	0.68	1	3
Level of accuracy of the inspections	1 = extremely low, 3 = adequate, 5 = too much	2.14	0.84	1	4
Interruption to operations	1 = very little, 3 = acceptable, 5 = too much	2.74	1.07	1	5
Cost of inspections	1 = extremely low, 3 = adequate, 5 = too high	2.73	1.03	1	5
Time required to perform an inspection	1 = too little, 3 = adequate, 5 = too much	2.61	0.92	1	5

As mentioned by a number of previous studies (Cheng et al., 2009; Yuan et al., 2016; Moon et al., 2018), precise, rapid, and real-time monitoring of the behavior of temporary structures components is necessary, as it is far more efficient than performing inspection and monitoring tasks manually. Though applying technologies on temporary structures requires that stakeholders put more effort into purchasing and maintaining devices, as well as training of operators, the safety impacts of such a system, such as ensuring structural integrity, avoiding incidents through real-time monitoring, and early warnings, are beneficial. However, a detailed cost-benefit analysis should be conducted to examine the feasibility of such an application.

2.6.3 Methods of Improvement

With respect to the opportunities to improve the safety performance of temporary structures, as presented in Figure 2.3, frequent inspection and maintenance during operations was the measure most often selected by the respondents, followed by better worker training, more education on designing temporary structures, improved regulations and standards, and use of innovative technology.

Eight participants provided additional suggestions for improvements, five of which mentioned the standards and requirements for temporary structure designers/engineers. These comments emphasized the importance of proper delineation of responsibilities of temporary structure designers/engineers in the design process, as well as the selection process. To be specific, detailed qualification standards for temporary structure designers/engineers is expected. Currently, for typical temporary structures such as scaffolding and concrete formwork, OSHA requires that they shall be designed by a qualified person/designer (OSHA 29 CFR 1926.451(a)(6) and 1926.703(b)(8)(i)). A qualified person is defined as one who, “by possession of a recognized degree, certificate, or professional standing, or who by extensive knowledge, training and experience, has successfully demonstrated his ability to solve or resolve problems relating to the subject matter, the work, or the project” (OSHA 29 CFR 1926.32(m)). No preferred qualifications of a temporary structure designer in terms of education and work experience are described in the current form of regulations. Furthermore, more code enforcement is recommended to make sure temporary structures are built conforming to the design and standards.

Other respondents mentioned that cross-training opportunities for engineers are necessary, as many structural engineers may not have adequate knowledge about construction engineering, whereas construction engineers may lack knowledge about designs. Facilitating communication among designers, construction engineers, and field personnel is also very important. Field personnel should acknowledge the tolerances of the designed structures to be well prepared for accident prevention. Lastly, one respondent commented that an allowance for temporary structure design should be included in the bid and assessed as part of the selection process.

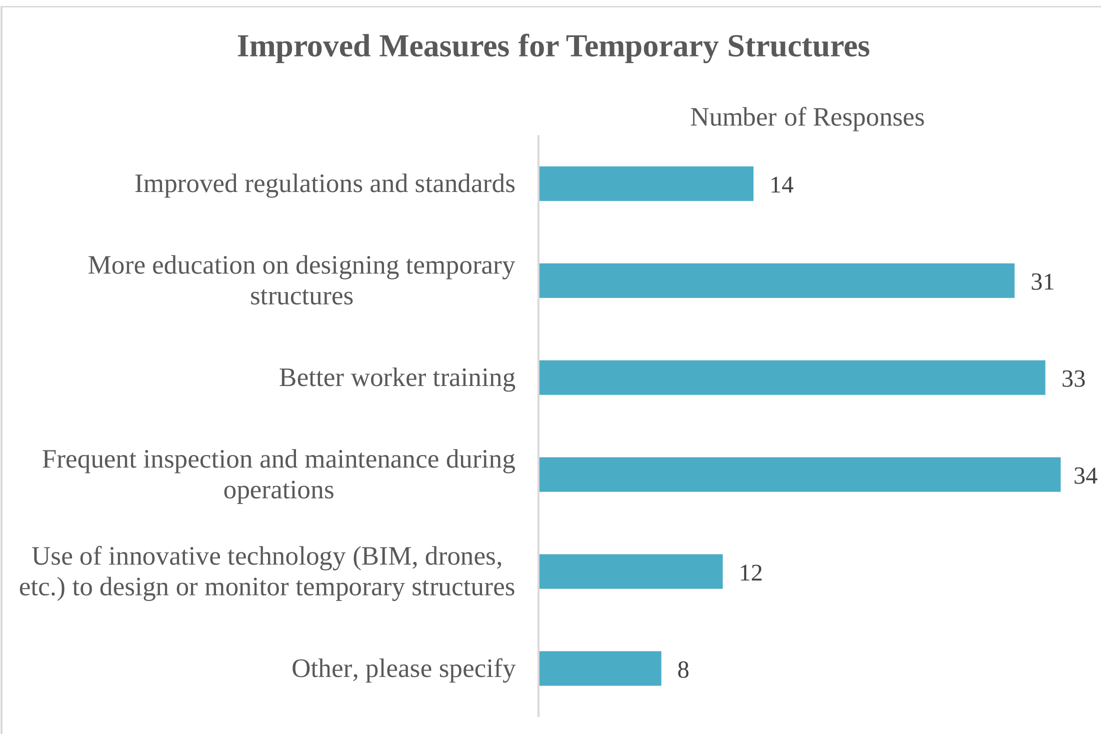


Figure 2.3. Improvement Measures for Temporary Structures *(n = 46)*

When asked about the features that construction technology, such as BIM, could be helpful for when designing temporary structures, more than half (52%) of the participants felt that technology could offer better ways to identify safety hazards. Effective communication with contractors and other stakeholders, and design deficiency identification were supported by 52% and 46% of the participants, respectively. Furthermore, 35% of the participants voted for design modifications based on safety considerations.

For controlling and monitoring of temporary structures in the construction phase, the respondents were invited to rate the importance of identified technology selection criteria (Table 2.2) using a five-point Likert scale starting with 1 for not at all important, 2 for slightly important, 3 for moderately important, 4 for very important, and 5 for extremely important. The relative importance index (RII) method was used to determine the relative importance of each technology selection criteria. The RII method is a non-parametric technique that has been widely used for responses received for structured questions with ordinal scales in determining the relative importance of various measures (Waris et al., 2014), such as important skills for project leaders (Odusami, 2002) and delay factors for construction projects in Turkey (Gündüz et al., 2012). The RII of each criterion can be determined based on Equation (*1*) (Waris et al., 2014):

$$\text{RII} = \frac{5n_5+4n_4+3n_3+2n_2+1n_1}{5N} \quad (1)$$

where n_1 = the number of respondents who selected "not at all important"; n_2 = the number of respondents who selected "slightly important"; n_3 = the number of respondents who selected "moderately important"; n_4 = the number of respondents who selected "very important"; n_5 = the number of respondents who selected "extremely important"; and N = the total number of respondents.

As a result, the ranks of the importance of selection criteria are determined based on the results obtained with the RII method. The results are shown in Table 2.4. It is evident that providing desirable results in terms of accuracy and robustness, with an RII of 0.850, is the most important criterion. This criterion is followed by easy to use and implement (0.845) and quality of data (reliability) (0.819). Training requirements (0.727), cost of installation and maintenance (0.718), and cost of purchase (0.705) were rated to be the three least important items when making decisions to select technologies for monitoring the performance of temporary structures.

It is noteworthy that when selecting appropriate technologies for the tasks of inspecting and monitoring temporary structures, besides those criteria related to technologies specifically (Table 2.2), other project or stakeholder factors would also affect the selection, such as the size of the project, complexity of the temporary structure, experiences of the designers and constructors, etc.

Table 2.4. Ranking of Importance of Technology Selection Criteria for Monitoring Temporary Structures *(n = 46)*

Technology Selection Criteria	**RII**	**Priority**
Providing desirable result (level of accuracy, robustness, etc.)	0.850	1
Easy to use and implement	0.845	2
Quality of data (reliability)	0.819	3
Time efficiency in data processing and interpretation	0.795	4
Time efficiency in data acquisition	0.791	5
Meets required need(s); has required features	0.786	6
Less disruption to operations	0.773	7
Training requirements	0.727	8
Cost of installation and maintenance	0.718	9
Cost of purchase	0.705	10

2.6.4 Technology Usage in General and Technology for Temporary Structures

Two questions were asked in the technology usage section of the questionnaire. The first question is related to the current usage of construction technology on site in general, not necessarily specifically related to temporary structures. It was found that BIM/VDC, drones, laser scanning, and video/photo logs are the most frequently used construction technologies on sites. More than half of the participants indicated that they had observed the selected technologies in use on sites. Based on the responses, BIM/VDC is used for generating building models, modeling structural steel framing, coordinating in the shop drawing process, performing clash detections, and other activities. Drones are also used for multiple purposes, such as monitoring the structural stability of existing structures, documenting the structure erection process with photos/videos, and conducting logistics planning, among others. Additionally, laser scanning was frequently used for quality control purposes, such as measuring as-built tolerance of a retaining wall, helping perfect flooring by assessing floor flatness and levelness, and monitoring wall movement. Laser scanning is also used for identifying site constraints and documenting building layouts. Video/photo logs taken at sites are mainly used to document project conditions.

On the other hand, the second question focused on technologies for temporary structures. Participants were invited to select from the identified technologies (Table 2.1) based on their opinions whether it could be helpful with the performance of temporary structures. As shown in Table 2.4, BIM/VDC was supported by 71% of the participants, which was viewed as the most promising technology to improve the performance of temporary structures. Additionally, sensor-based technology and video/photo logs were supported by 59% and 44% of the participants, respectively. Many participants pointed out that not many technologies have been applied to temporary structures, and indicated some concerns about applying construction technologies on temporary structures. For instance, laser scanning data may not provide enough accuracy to detect structural displacement for temporary structures due to dimensional limitations. Furthermore, one participant pointed out that BIM is a good tool to facilitate design coordination among multiple trades, but it may not be necessary for temporary structures.

2.6.5 Additional Comments

Some of the participants provided accompanying comments that aimed to explain the reasons for temporary structure failures and pointed out ways to improve temporary structures in general. Many comments related to qualifications of designers and constructors of temporary structures, and communications among involved parties. For example, one participant commented that, "Issues occur too often when underqualified contractors bypass safety inspections by designers and do not adequately use the design product provided by the designer. This action commonly results in an accident, injuries, loss of life, and legal troubles for all involved." The respondent added that there must be assurance that the contractor and designer are qualified for the work, and that peer reviews of design work are also required and performed by a reviewer who is qualified for the work. Another participant expressed that, "Temporary structure design requires close coordination with field forces and their capabilities. Just having an SE (structural engineering license) does not qualify someone as a temporary structures engineer."

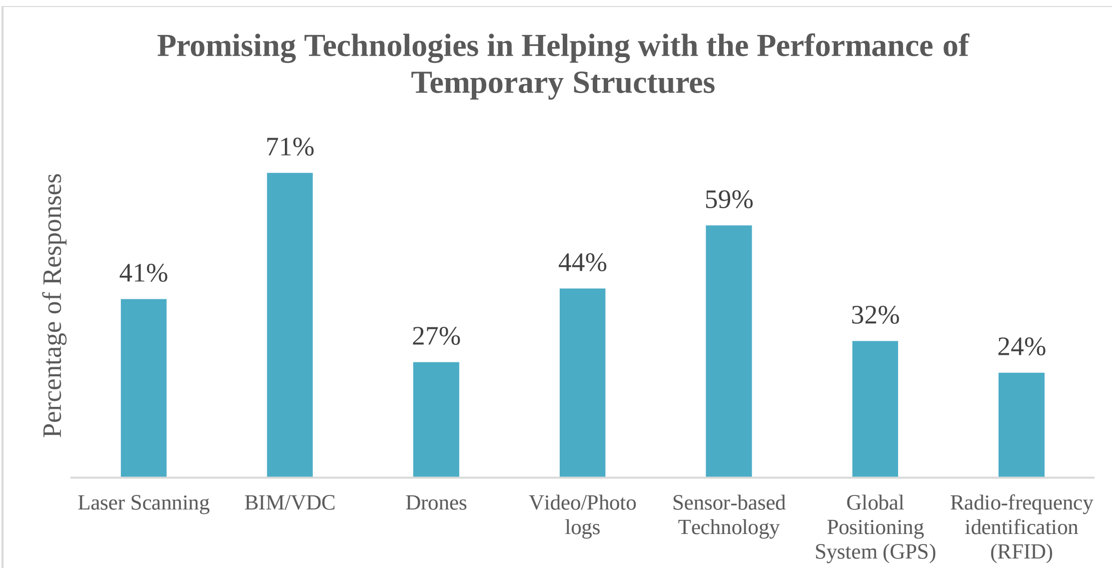


Figure 2.4. Promising Technologies for Helping with the Performance of Temporary Structures *(n = 46)*

A participant who works as a contractor commented that, "We take the design and construction of temporary structures very serious. As a contractor, we understand that the liability falls back onto us if something goes wrong. 95% of the time that I have seen issues with temporary structures it is because someone was trying to save time and/or money and they cut corners". Apparently, such practice may lead to multiple issues such as poor designs or overloading structures that result in temporary structure failures.

Some of the participants also recognize the issues of material reuse in temporary structures. For instance, one participant mentioned that, “Many of the materials used in temporary structures are re-used over multiple applications. Inspection of parts and pieces to guarantee proper working order is lacking.”

2.7 Research Validation, Reliability and Limitations

Validation of the research process and results is a fundamental element to ensure the quality of a research study (Lucko and Rojas, 2010). Internal and external validity are two main components of the validation process (Abowitz and Toole, 2009; Lucko and Rojas, 2010). Internal validity is related to the concept of causality and focuses on testing whether a causality relationship can be established within the data. According to Lucko and Rojas (2010), establishing causality is challenging for construction researchers, as true causality can only be established under a carefully controlled, laboratory-like environment, which occurs most likely in an experimental study design. In the present study, using a mix of non-probability sampling techniques with nonrandom sampling selection introduces selection biases in data collection, which inhibits the identification of causal relationships. Therefore, the internal validity of the present study is limited because the adopted research method lacks randomness and controls for potential confounding factors.

On the other hand, external validity is related to the concept of generalization and examines whether the research findings could be generalized to a broader population (Abowitz and Toole, 2009). In other words, external validity requires that the selected sample be representative of the population (Lucko and Rojas, 2010). As for the present study, since the contact list of the target population is unknown, randomizing the sampling procedure is infeasible to achieve. Additionally, through a mixed-method approach in data collection, the survey response rate is unknown and the sample size of the study is relatively small (n = 46). The results received suffer from a number of the abovementioned biases and may not allow for making inferences to a larger population. The findings and the overall conclusions of the present study are based on the collected samples only and might be inconclusive. However, the survey respondents were highly experienced in the industry and were familiar with temporary structures, as more than half of them are from temporary structure related professional groups from ACI and ASCE. The authors believe that the study findings provide a valuable indication of professionals' viewpoints of the current practices related to temporary structures, and using construction innovations on temporary structures.

With respect to reliability, the study adopted the most commonly used Cronbach's α (Cronbach, 1951) to examine the internal consistency (Lucko and Rojas, 2010). An α value of 0.70 or higher suggests a reliable rating scale (Nunnally, 1994). The Cronbach's α was measured for the question that is related to current practices regarding inspections of temporary structures, in which multiple measurement items were assessed based on a Likert scale. As a result, the Cronbach's α is 0.76, which is greater than the suggested acceptable level (0.70). The results of the analysis suggest high reliability of the survey results.

The limitations of the present study are mainly due to the research method utilized (only adopting a single method of data collection) and the sampling techniques (non-probability sampling). Future research is encouraged to adopt a mixed or multimethod approach, as applying such an approach enhances the reliability and validity of the study conclusions (Abowitz and Toole, 2009). The authors also recommend investigating the research questions with more professionals who are familiar with temporary structures and comparing the results with those found in the present study.

2.8 Conclusions and Recommendations

Interest in applying technologies in safety management in the construction industry, which aims to improve occupational safety, is growing. However, the majority of efforts have been undertaken for permanent structures rather than temporary structures. Given the importance of temporary structures and the number of workers who have to work with temporary structures when constructing permanent structures, it is necessary to identify deficiencies in the current practices, explore room for improvement, and investigate the potential for using technologies on temporary structures. The present study contributes to the body of knowledge by investigating the current practices related to temporary structure design and construction, and gaining opinions from industry and academic professionals with respect to technology applications to improve the design quality and safety performance of temporary structures.

The findings of the study indicate that a large percentage of design and construction professionals agree that, currently, the industry pays less attention to temporary structures when compared to permanent structures. To be specific, 91% of the participants held this perspective for temporary structure design and planning, while 74% of the participants felt the same way for temporary structures during the construction phase. In the future, additional care should be paid to temporary structures during the design/planning phase and the construction phase, which was supported by more than 85% of the participants. Since many temporary structure failures have occurred due to inadequate procedural causes (e.g., insufficient design/inspection reviews), effective quality control measures for designs and inspections should be set up. Especially in the current investigation and monitoring practices of temporary structures on site, participants feel that the frequency of temporary structure inspection on site is not enough to ensure the safety and structural integrity of the temporary structures. It is worth noting that temporary structure elements are often used repeatedly and, as a result, subject to loss of capacity due to deterioration in the quality of the elements (Barbosa et al., 2014). Careful assessments of the reliability of members should be performed before designing or installing temporary structures. Furthermore, regulations and standards related to qualifications of designers, and delineating responsibilities and duties of the parties involved in the design and construction of temporary structures, are anticipated to improve the overall performance of temporary structures.

With regard to technology applications to enhance the performance of temporary structures, BIM/VDC is rated to be the most promising technology to improve designs. A majority of the survey participants (71%) agreed that BIM/VDC provides a better platform to identify safety hazards, conduct effective communications among stakeholders, and recognize design deficiencies. Furthermore, sensor-based technology, video/photo logs, and laser scanning have the potential to assist with inspecting and monitoring temporary structures when they are in use. To select an appropriate technology to perform the inspection and monitoring task, consideration of whether the technology provides a desirable result, whether it is easy to use and implement, and whether it provides quality data are the three most important criteria to consider based on the results obtained through the RII method. Apart from the selection criteria related to technology, project characteristics such as the size of the project and experiences of designers and constructors should also be considered when making the selection decision.

Though participants generally hold a positive attitude towards the possibility that technology applications could be helpful in improving the safety performance of temporary structures, they also expressed many concerns regarding the applications. The participants are concerned primarily because currently not many technologies have been applied to temporary structures and engaging technology requires extra resources and effort in terms of costs of purchase and maintenance, and cost and time spent on training of operators. Future research is recommended to develop more technology applications to assist either temporary structures design and/or inspection tasks, apply the technologies in the field, and provide detailed analysis results to confirm the effectiveness of the developed technology applications.

3. MANUSCRIPT #2 – BIM FOR TEMPORARY STRUCTURES: A BIM-API FOR CONCRETE FORMWORK

The content of Chapter 3 is an adapted and extended version of the following conference paper.

> Jin, Z. & Gambatese, J. 2019. BIM for Temporary Structures: Development of a Revit API Plug-in for Concrete Formwork. *Proceedings of the Canadian Society for Civil Engineering (CSCE) Annual Conference*, Laval (Great Montreal), Canada, 12-15 June 2019.

The research findings described in Chapter 2 (Manuscript #1) suggest that more attention should be given to temporary structures, and industry professionals hold generally positive attitudes toward technology use on temporary structures. Among all the technologies, BIM/VDC was identified as one of the most promising technologies to be applied on temporary structures. Chapter 3 explores ways to incorporate safe design procedures and consideration within BIM authoring tools, and enabling formwork model automation, with an objective to improve the design and model quality of temporary structures, and to improve the overall worker safety and health. The type of temporary structures focused on is concrete formwork.

3.1 Abstract

As one of the most promising developments, BIM enables the possibility of automating the design process. Prior research efforts related to BIM have largely focused on permanent design components with minimal attention given to temporary structures, such as concrete formwork and scaffolding. Nevertheless, the design processes for temporary structures are repetitive and often tedious, which require consideration of multiple parameters of individual permanent components, the latest design standards, design methods, procedures, and available materials. This manuscript proposes a BIM-based tool to help with planning and designing concrete formwork, and generating the design. The streamlining tool integrates the information associated with individual elements in BIM models with design processes recommended by the American

Concrete Institute (ACI) through an Application Programming Interface (API) in the BIM extension. The workability of the proposed tool was demonstrated through a case study. The effectiveness of the proposed tool and its potential in addressing worker safety and health was verified by industry professionals. Using the tool, planners will be able to decide the most applicable formwork design based on the design of the permanent facility along with the availability of construction materials, site conditions, and safety considerations. The research also provides a new tool for contractors when planning concrete operations and extends the BIM design scope.

3.2 Introduction

Among different types of temporary structures, concrete formwork is extensively used in the industry. Formwork is used for concrete construction to support permanent concrete forming and curing until the structure gains sufficient strength to support itself, as well as to support construction live load. The cost of formwork can be significant, it often accounts for 40% - 60% of the entire cost of cast-in-place concrete projects (ACI, 2014a). Proper designing, planning, placing and removing formwork is crucial to ensure the success of concrete projects. However, the safety record of concrete construction is relatively poor; about a quarter of all construction failures involve concrete construction (Lew, 1976).

Moreover, inadequate consideration has been given to temporary construction structures in the industry (Gilbertson et al., 2011; Jin and Gambatese, 2020). Studies have shown that if designers devote sufficient effort to the design of formwork or other temporary structures, worksite safety could be improved. For example, a study performed by the Health and Safety Executive in the UK (Bennett, 2004) showed that among all the investigated cases related to temporary structures, about one-sixth of the accidents could have been prevented if designers took enough action in the original design to improve safety. Similarly, researchers from California State University-Long Beach, after analyzing 435 accident case reports from the federal OSHA, concluded that insufficient design is one of the statistically significant causes of formwork-related injuries (Haduong et al., 2018). Other major factors that contribute to formwork failures include lack of monitoring during formwork erection and communication confusion among stakeholders (Hadipriono and Wang, 1986). Additionally, as suggested by Sheehan and Corley (2013), improved communication and organization of project documents among stakeholders could have helped to prevent an incident through the investigation of the formwork collapse when building a multi-story parking garage. It is apparent that approaches to improve the design quality of formwork and to facilitate communication and collaboration are essential to ensure site safety during formwork construction.

In recent years, BIM has been widely adopted by designers and contractors during the early stages of construction projects since BIM creates a collaborative environment and enables seamless information exchange among various stakeholders (Singh et al., 2011). BIM has changed the way buildings are designed, constructed, and operated, and has changed the traditional workflows and project delivery processes (Hardin and McCool, 2015). However, temporary structures are commonly not clearly delineated and planned in the building drawings or BIM models (Kim and Ahn, 2011) and the majority of past research efforts have put an emphasis on permanent structures. Only limited research has given attention to temporary structures, such as safety railings for fall protection (Zhang et al., 2015), temporary stair towers for roof construction activities (Kim and Cho, 2015), and scaffolding design and plans (Kim and Teizer, 2014; Kim et al., 2018a). More importantly, only a small portion of research studies have targeted concrete formwork (Meadati et al., 2011; Chi et al., 2012; Kannan and Santhi, 2013; Singh et al., 2017) and a limited number have proposed conceptual models for formwork planning (Chi et al., 2012; Singh et al., 2017). Consistent with prior research studies, the findings from Manuscript #1 also indicate that BIM is the most promising construction technology to improve the safety performance of temporary structures, especially through effective safety hazard and design deficiency identification and improved communication.

In addition, it has been shown that safety guidelines, standards, and best practices related to formwork designs can be successfully incorporated with the existing multi-dimensional models in BIM (Zhang et al., 2011; Zhang et al., 2015; Yuan et al., 2019). Given the importance of concrete formwork in the industry and the fact that designing and planning temporary structures requires excessive manual effort, the development of a BIM-based tool to help designers automate the design process with safety rules, which also benefits planners and other stakeholders, is in high demand.

3.3 Background

3.3.1 Formwork Design

Concrete forming practices may differ from one country to another and even from one region to another in the same country due to predominant local material use, material availability from suppliers/manufacturers, and contractor preference (ACI, 2014a). Except for unusual or complex structures, in general, the contractor is responsible for planning and designing the formwork. The detailed work may involve multiple parties including formwork engineers, form manufacturers, form suppliers, and formwork specialty subcontractors. As for complex structures, the engineer/architect who designed the concrete structure and specifications may also get involved and be partly responsible for formwork design and planning.

Guides, standards, and specifications on formwork design and planning have been published by different professional associations and regulatory agencies. Recognizing that design codes and standards were mostly silent on the subject of construction loads, in 2002, the ASCE published "Design Loads on Structures during Construction" to provide designers and constructors guidance on the minimum design load requirements that need to be considered during the construction of buildings and other structures. This reference manual describes the minimum loading and pressures for which the formwork shall be designed. With respect to concrete, concrete formwork, and shoring, OSHA provides requirements in Subpart Q (concrete and masonry construction) (OSHA 29 CFR 1926). In particular, in OSHA CFR 1926.703(b)(8)(i), it is stated that "the design of the shoring shall be prepared by a qualified designer and the erected shoring shall be inspected by an engineer qualified in structural design." Targeting concrete formwork systems, Chapter 6 in the book "Building Code Requirements for

Structural Concrete (ACI 318-11)" (ACI, 2011) covers general guidance of designing formwork. The book "Guide to Formwork for Concrete (ACI 347R-14)" (ACI, 2014b) provides detailed guidance for formwork design and construction, and another book published by ACI (2014a) provides detailed step-by-step procedures to design different components of formwork systems.

The formwork design process requires tedious effort (Singh et al., 2017; Hyun et al., 2018), which consists of rigorous structural analysis. Furthermore, to facilitate the design process and ease a form designer's work, several books provide design tables that indicate calculated safe spans for typical formwork designs. Even though design tables are easy to use, the formwork designs obtained may not be suitable for all site conditions. With respect to formwork plans, because there is no standard and formal practice to generate temporary structure plans in the industry, the planning process is often performed manually and based on the planner's own experience, which is commonly subjective, time-consuming, and error-prone (Kim and Fischer, 2007; Zhang et al., 2011).

3.3.2 BIM Applications for Formwork

With the development of construction innovations, considerable research effort has been devoted to exploring ways to facilitate the formwork design and planning process and to improve worker safety using BIM. BIM-based planning of temporary structures such as formwork and scaffolding has the potential to reduce worksite accidents (Sulankivi et al., 2010). But the library of BIM objects for temporary structures is minimal, and the safety standards and regulations associated with temporary structures are not seriously considered in BIM during the design and planning phase (Sulankivi et al., 2010; Chi et al., 2012).

Some studies focused on developing BIM objects for temporary structures. For example, Meadati et al. (2011) developed a concrete formwork repository and discussed its potential for incorporating other functions to assist safety design and planning, such as design visualization, quantity takeoff, cost and constructability analysis, and shop drawing generation. Chi et al. (2012) proposed to develop formwork BIM objects with safety features and constructability elements.

Few studies considered incorporating standard design procedures into the design process. Studies performed by Singh et al. (2016; 2017) proposed frameworks to link formwork calculation tools with BIM models to automate formwork design processes. However, their studies were only at a conceptual level and the researchers did not consider constructability and safety issues. Hyun et al. (2018) utilized the international open-BIM standard - Industry Foundation Classes (IFC), and proposed a BIM-based automatic formwork design system. The system could be used to generate various design alternatives and to select the best design based on costs. However, the proposed approach was not a streamlined process and it was not user-friendly.

Concentrating on modular formwork, Romanovskyi et al. (2019) proposed a BIM-based decision-support system for designing concrete formwork with the help of Dynamo, a visual and open-source programming environment for Revit. The end results of the proposed system are MS Excel spreadsheets that contain design results in terms of properties, dimensions, locations, and other parameters of formwork components.

Other BIM-related studies on concrete formwork attempted to incorporate additional features. For instance, Kannan and Santhi (2013) conducted constructability assessments of climbing formwork systems in BIM. Khosakitchalert et al. (2019) developed an automatic quantity takeoff approach for form components using Dynamo. Lee et al. (2021) developed a prototype that aims to enable formwork design automation based on 3D BIM data converted from 2D CAD data of formwork design. In their study, Lee et al. developed a formwork layout algorithm to generate a formwork design automatically. With the generated layout, the size and quantity of form components could be calculated.

In summary, none of the current BIM-based formwork approaches considers worker safety and health during the design and planning phase, and provides a streamlined and user-friendly way to improve the design and model efficiency for concrete formwork. Another notable drawback of present approaches is that none of them attempted to generate BIM models automatically based on the obtained formwork design results, which inhibit the realization of the visualization features provided by BIM.

Past research studies have successfully utilized the benefits of parametric modeling to incorporate additional functions in the design and planning phases. For example, for sustainability considerations, Bank et al. (2010) proposed to integrate a BIM model with sustainability indicators in a system dynamics decision-making tool for alternative evaluation and optimization. Additionally, as mentioned by Wu and Issa (2012), the LEED Automation program initiated by the U.S. Green Building Council (USGBC), provides opportunities to streamline cloud-BIM engagements with the LEED certification process. In 2016, Oti et al. developed a BIM extension that enables sustainability appraisal for structural design options. Additionally, other developed BIM extensions also show promising results in expanding the BIM design capabilities and enabling nD building performance measures, such as preconstruction operations (Karan and Irizarry, 2015), facility management/asset management (Lin et al., 2014; Farghaly et al., 2018), supply chain management (Irizarry et al., 2013), architectural visualization (Du et al., 2018), safety risk identification, prevention and control (Yuan et al., 2019), among others.

Given the achievements in extending BIM functions by using API implementations or open-source visual programming platforms such as Dynamo for Revit in previous research, integrating formwork design procedures and safety rules, and enabling automation in model generation with BIM models is promising. Such integration may improve design and model quality, save labor and time, and have the potential to improve worker safety and health during the construction phase.

3.4 Research Objectives

Taking advantage of API capabilities, this study attempts to make a direct link between AutoDesk Revit, a BIM modeling software, and formwork design and planning through the development of a Revit API. To limit the scope of the present BIM-API development, the study concentrated on timber formwork systems for elevated concrete floor slabs and concrete walls. Timber concrete formwork systems are extensively used in the industry as they are easy to erect in the required size and shape, easy to handle and dismantle, and relatively inexpensive compared to steel and aluminum systems. The objectives of the present study described herein are to:

1) Develop a framework that integrates formwork design procedures and safety rules with BIM models,
2) Develop a BIM-API to assist with formwork designs and model generation,
3) Implement the proposed BIM-API on a selected case study, and
4) Investigate the workability and effectiveness of the proposed BIM-API, and its potential to improve worker safety and health.

3.5 Conceptual Formwork Design and Model Framework

As introduced in Eastman (2011), BIM models are primarily object-based parametric models that consist of customized parametric objects and their relational structures with other objects. To achieve the goal of automating the formwork design model process, the key geometric parameters of 3D BIM form components could be determined through a systematic design process. And, the location of the created formwork components, in relation to their hosts (slabs/walls), could be determined using the coordinate system in a BIM environment.

The proposed BIM-based formwork design framework is depicted in Figure 3.1. In the formwork design phase, the first step is to retrieve the required parametric information of the design components, such as concrete slabs or walls, from the existing 3D BIM model for formwork design. The second step involves using the extracted data from the first step to perform the formwork design based on the designers' initial assumptions and material availability. The formwork design process follows the procedures recommended by ACI (ACI, 2014a; b). During the design process, safety recommendations that enable safer design and planning are provided to users. The safety recommendations are extracted from the formwork design standards contained within the OSHA standards and other industrial formwork safety best practices. After the design is complete, the proposed formwork design will be modeled with the existing 3D model.

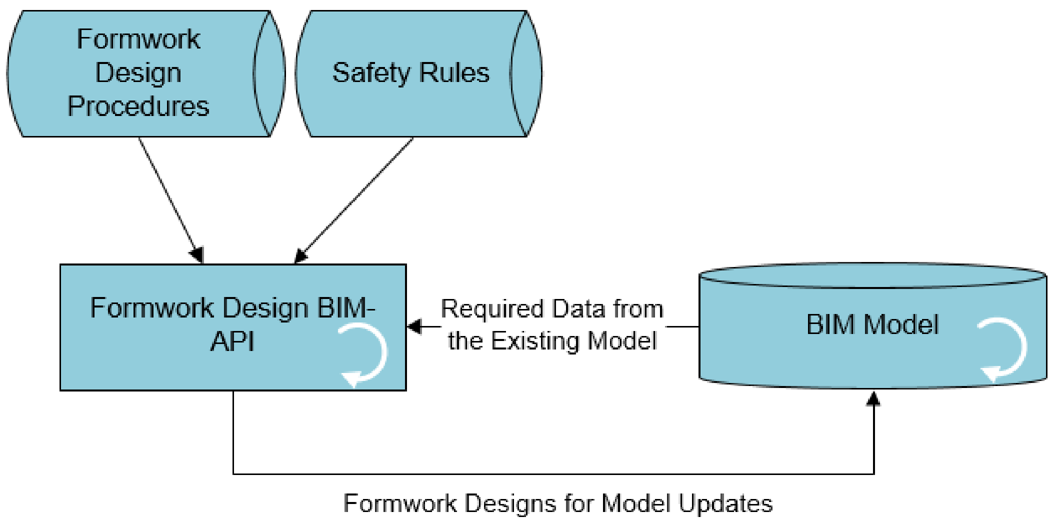


Figure 3.1. Proposed BIM-Based Formwork Design and Model Framework

3.6 Formwork Design BIM Plug-in Development

The focused types of concrete structures of the present study are elevated concrete slabs and concrete walls. The design procedures of slab formwork and wall formwork are described in the following sections, followed by the safety rules that are applicable to formwork design and planning.

3.6.1 Slab Formwork Design Procedures

Design of timber formwork for slabs consists of a systematic structural analysis of sheathing, which is used to retain the concrete, and members to support the sheathing firmly in place during concrete placement and curing. As suggested by ACI (2014a), the basic steps of slab formwork design include the determination of:

- design load (both live load and dead load),
- sheathing thickness and spacing of its supports (joist spacing),

- joist size, and spacing of joist supports (stringer spacing),
- stringer size and span length (shore spacing),
- shore spacing and size,
- bearing stress checks, and
- lateral bracing design.

The detailed process and data flow of slab formwork design can be found in Figure 3.2. The figure shows the process for wood formwork; the process is similar if other formwork materials (e.g., steel, aluminum) are used, with slight variances in the capacity checks and design calculations. It is worth mentioning that sheathing or lumber adjustment factors and safety factors are applied when designing timber formwork to ensure that the formwork is strong enough to support the design load and lateral pressure generated by freshly placed concrete, construction live loads, and environmental loads.

3.6.2 Wall Formwork Design Procedures

Similar to slab formwork design, wall formwork design consists of steps to determine lateral design load and for the design of different wall formwork components, such as sheathing, studs, wales, and ties. However, compared to designing slab formwork, the determination of the design load for wall formwork is relatively complex, and requires actual field data during concrete placement, including the rate of concrete placement, temperature, and admixtures and cement blends used. Therefore, a user-friendly, accurate, and time-saving tool could be extremely useful either to design or to verify wall formwork designs. The design procedures and data flow of wall formwork design can be found in Figure 3.3.

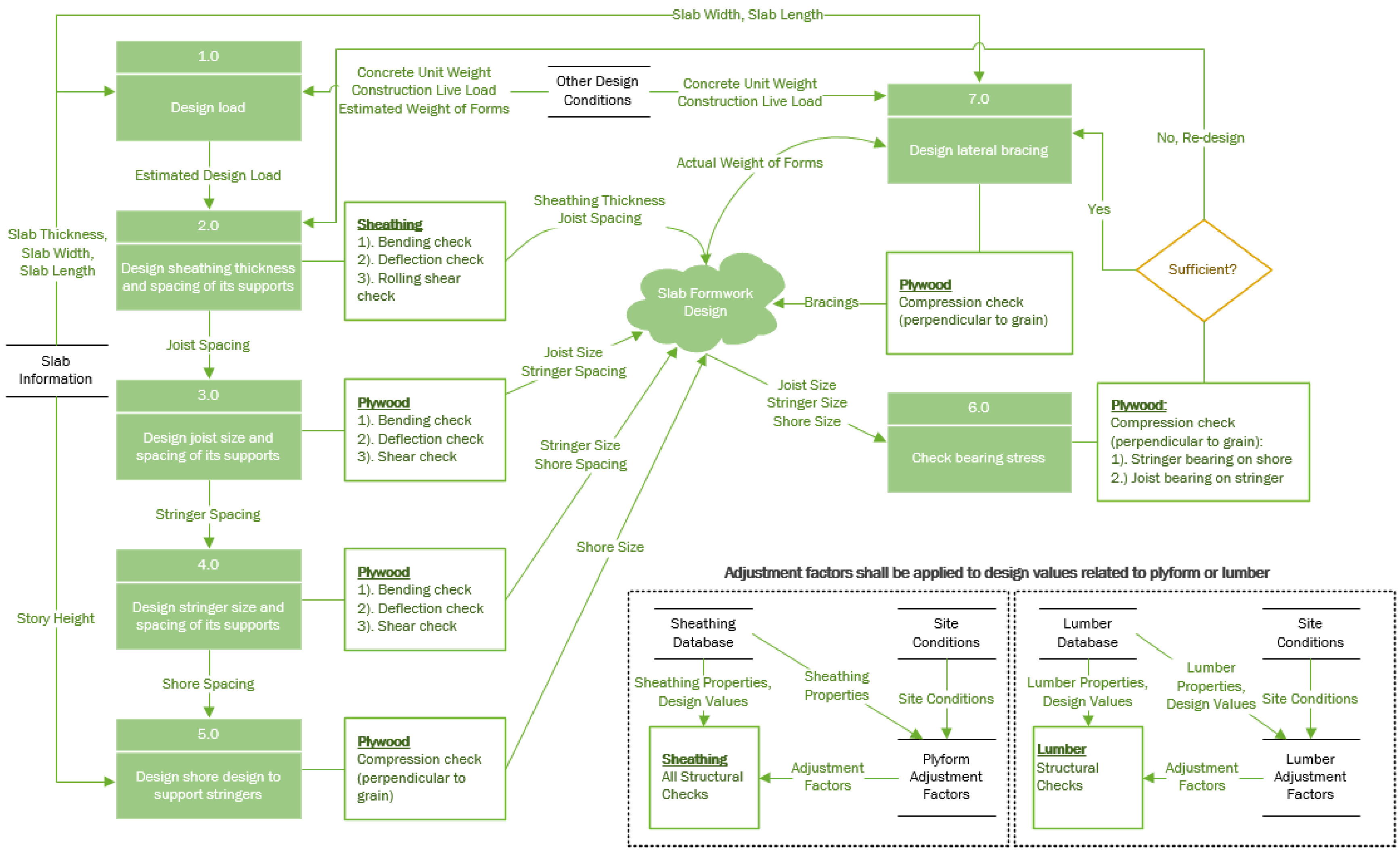


Figure 3.2. Slab Formwork Design Procedures (Wood Formwork)

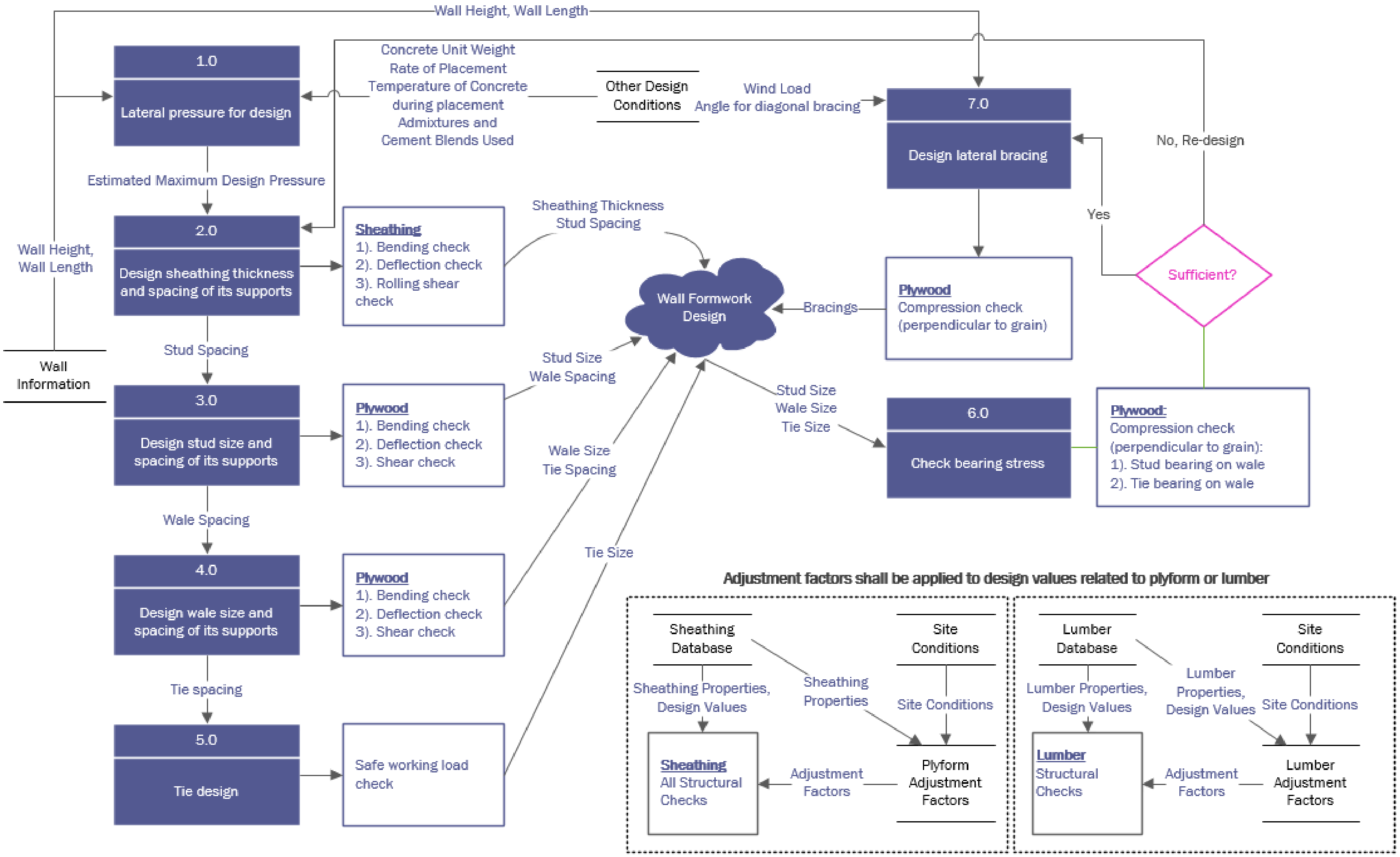


Figure 3.3. Wall Formwork Design Procedures (Wood Formwork)

3.6.3 Formwork Design Safety Rules

Regarding safety considerations applied to formwork designs, the researchers carefully searched the OSHA regulations and other safety guidelines. The search results revealed three categories of safety requirements related to formwork: design requirements for cast-in-place concrete, standards related to fall protection, and guidance about material handling. The incorporated safety rules and implemented measures in the proposed BIM-API are listed in Table 3.1.

As listed in Table 1.2, many construction workers lost their lives due to the failure of concrete formwork. Falls, which are identified as the leading cause of work-related injuries and fatalities in the construction industry (OSHA, 2012), could occur during formwork operations (OSHA, 1985; 2006; 2010). Falls are one of the major safety concerns for workers when working with formwork. As stated by OSHA (2004), "Each employee on a walking/working surface (horizontal and vertical surface) with an unprotected side or edge which is 6 feet (1.8 m) or more above a lower level shall be protected from falling by the use of guardrail systems, safety net systems, or personal fall arrest systems." Therefore, in the proposed BIM-API, if formwork is designed to be elevated to 6 feet or more above the lower level, the system provides a reminder that fall protection systems, such as guardrails, safety net systems, personal fall arrest systems, should be installed or provided to workers.

Besides worker safety, another concern related to concrete formwork operations is worker health. Concrete formwork construction is recognized as one of the work operations in which workers have a high risk of developing Musculoskeletal Disorders (MSDs) (Spielholz et al., 1998), as form workers are frequently exposed to awkward postures due to motions like heavy material lifting. Therefore, suggestions to address worker health are necessary to prevent and control occupational illnesses and injuries, such as MSDs. The recommended maximum weight of a load carried by one worker is 51 pounds (OSHA, 2015); exceeding the recommended load would increase the risk of back injury significantly (Waters et al., 1994). Thus, to address the health concern of workers while working with forms, if the proposed BIM-API provides information for users whether the weight of design component(s) exceeds the recommended maximum load. With such information, users could decide if they have available lightweight components to substitute in the original design. In this case, they may re-run the design procedures to include lighter components, or keep the original design and have more than one worker lift the components during the construction phase.

Table 3.1. Safety Rules Used in the Proposed BIM-API

Category	Standards/Guidance Details	Measures Taken in the Proposed BIM- API
Requirements for cast-in-place concrete (OSHA, 1996)	1926.703(a)(1) – “Formwork shall be designed, fabricated, erected, supported, braced and maintained so that it will be capable of supporting without failure all vertical and lateral loads that may reasonably be anticipated to be applied to the formwork”.	The API is designed to follow the design procedures recommended by ACI
Fall protection (OSHA, 2004)	1926.501(b)(1),1926.501(b)(2), 1926.501(b)(5),1926.451(g) – “Each employee on a walking/working surface (horizontal and vertical surface) with an unprotected side or edge which is 6 feet (1.8 m) or more above a lower level shall be protected from falling by the use of guardrail systems, safety net systems, or personal fall arrest systems.”	If formwork is designed to be elevated 6 feet or more above the lower level, remind users to plan for fall protection systems, and use appropriate fall protection systems during the construction phase
Material handling (OSHA, 2015)	Based on the lifting equation from the National Institute for Occupational Safety and Health (NIOSH), the recommended maximum load for manual lifting is 51 pounds.	If the selected formwork components exceed 51 pounds, recommend users to use lightweight components or remind users to use two or more people to lift the load

3.7 Revit-API Development

AutoDesk Revit was selected as the development platform for the proposed plug-in. The Revit plug-in for designing formwork systems was programmed using C# language in the .NET Framework (version 4.7.2). Two Revit API references, which are required to ensure the interaction between the external application and the Revit environment, are loaded in the BIM-API: RevitAPI.dll and RevitAPIUI.dll. Also, a plug-in manifest was written and added to the system so that Revit can read the plug-in at startup.

Figure 3.4 presents a flowchart of the proposed plug-in when designing and modeling formwork for a concrete wall or slab. It mainly consists of three steps: 1) user selection for a concrete wall or slab, 2) guided formwork design process, and 3) design automation after the design process is completed. The details about the three steps are described in the subsections below.

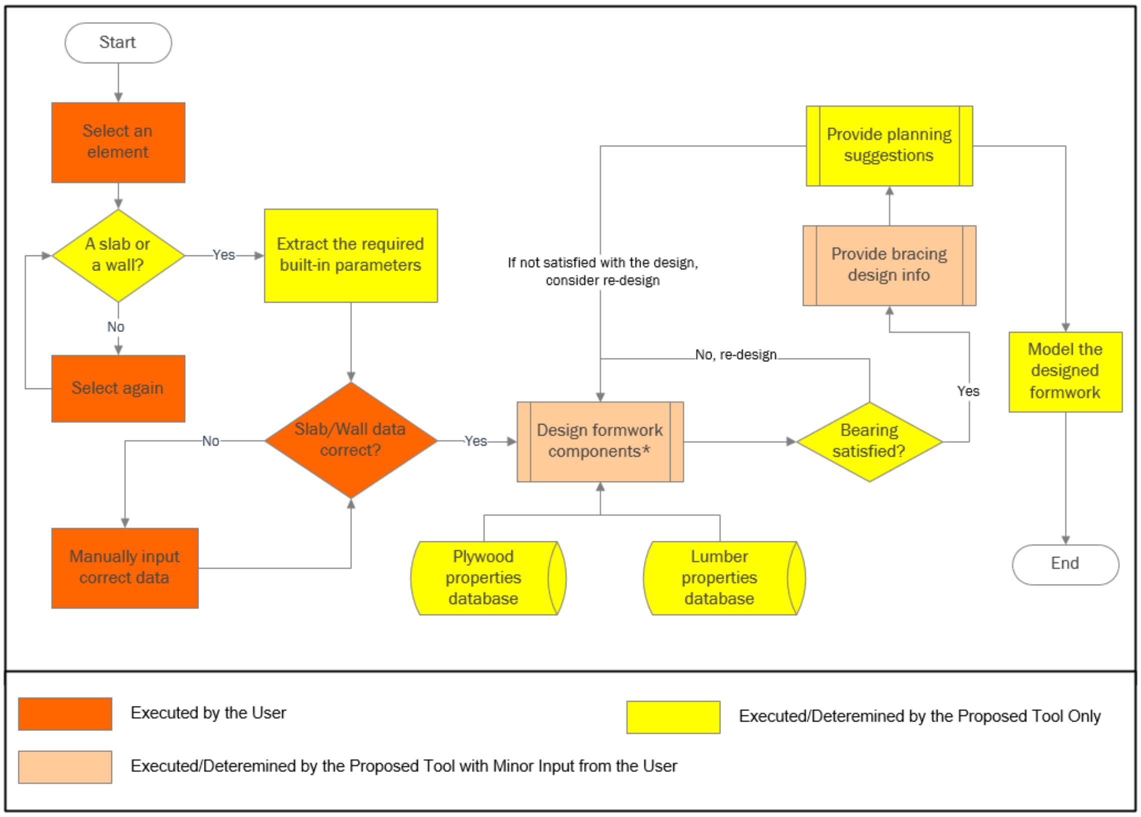


Figure 3.4. Flowchart of the Proposed Revit-API

3.7.1 Formwork Design for Concrete Slabs and Walls

Taking designing forms for concrete slab as an example, after opening the plug-in in Revit, the user makes a selection from the existing 3D model. If the selection is not an elevated slab, the user has to make another selection; otherwise, the application automatically extracts the parameters of the selected component.

Figure 3.5 provides the example code to filter user selection (both slabs and walls), and to extract the required information from the existing 3D BIM model. For slab formwork design, the built-in parameters retrieved include slab thickness, slab area, slab perimeter, slab height (elevation from the bottom of the slab to the top of the lower level), and slab geometric location in terms of slab center. Through the computation of the retrieved parameters, the slab width and length can be determined (currently, the extension is only applicable for rectangular-shaped concrete slabs). Similarly, when designing for wall formwork, the extracted information of the selected wall includes wall length, wall width, wall height, and the coordinates of the wall center. Once the user confirms the slab/wall data are correct, or manually enters the correct data, the user is guided through the systematic formwork design procedures (as shown in Figure 3.2 and Figure 3.3) to determine the appropriate size and spacing of form components.

```
using (Transaction start = new Transaction(doc))
{
    start.Start("Make a selection");

    Element e = SelectElement(uidoc, doc);

    // Filtered Element
    if (e.Category.Name == "Floors")
    {
        // Retrieve Parameter
        double slab_thickness_revit = GetParameterSlabThickness(e).AsDouble();
        double slab_area_revit = GetParameterSlabArea(e).AsDouble();
        double slab_perimeter_revit = GetParameterSlabPerimeter(e).AsDouble();
        double slab_height_revit = GetParameterSlabHeight(e).AsDouble();

        BoundingBoxXYZ bb = e.get_BoundingBox(null);

        Outline outLne = new Outline(bb.Min, bb.Max);

        XYZ SlabCenter = (bb.Min + bb.Max) / 2;

        Form_Slab_Welcome UI1 = new Form_Slab_Welcome(slab_thickness_revit, slab_area_revit, slab_perimeter_revit, slab_height_revit, SlabCenter);
        UI1.ShowDialog();
    }
    else if (e.Category.Name == "Walls")
    {
        double wall_length_revit = GetParameterWallLength(e).AsDouble();
        double wall_height_revit = GetParameterWallHeight(e).AsDouble();
        double wall_width_revit = GetParameterWallWidth(e).AsDouble();

        BoundingBoxXYZ bb = e.get_BoundingBox(null);

        Outline outLne = new Outline(bb.Min, bb.Max);

        XYZ WallCenter = (bb.Min + bb.Max) / 2;

        Form_Wall_Welcome UI2 = new Form_Wall_Welcome(wall_length_revit, wall_width_revit, wall_height_revit, WallCenter);
        UI2.ShowDialog();
    }
    else
    {
        TaskDialog.Show("Warning", "Please select a concrete slab or a wall to continue");
    }

    start.Commit();
}
```

For Slabs

For Walls

Figure 3.5. Example Code to Filter Element and Retrieve Required Parameters

In the system, the properties and reference design values of a pre-determined set of lumber and plywood were saved in .csv files, which serve as a formwork component database. The contained information for lumber includes nominal size, American standard size, area of section, moment of inertia, section modulus, approximate weight, and reference design values of bending, shear, compression, tension, and modulus of elasticity for different lumber species, grade, and nominal size. For plywood, which is widely used for sheathing, the contained information includes grade, thickness, moment of inertia, effective section modulus, rolling shear constant, approximate weight, and reference design values of bending, rolling shear, bearing, and modulus of elasticity for different plyform grades. Such information is then read by the Revit-API. Therefore, the user could select from the provided form components to start the design. If the system does not provide the option the user desires, he/she could add the corresponding detailed properties and/or design values in the .csv files. Figure 3.6 provides some sample rows of lumber properties used in the proposed Revit-API.

lumberID	nominal_b	nominal_d	standard_b	standard_d	finish_Lumber	areaSection_Lumber	I_Lumber	S_Lumber	weightlbperft_Lumber	size
R_02_01	2	4	1.5	3.5	Rough	5.89	6.45	3.56	1.3	2 x 4
S_02_01	2	4	1.5	3.5	S4S	5.25	5.36	3.06	1.3	2 x 4
R_02_02	2	6	1.5	5.5	Rough	9.14	24.1	8.57	2	2 x 6
S_02_02	2	6	1.5	5.5	S4S	8.25	20.08	7.56	2	2 x 6
R_02_03	2	8	1.5	7.25	Rough	11.98	54.32	14.73	2.6	2 x 8
S_02_03	2	8	1.5	7.25	S4S	10.87	47.63	13.14	2.6	2 x 8
R_02_04	2	10	1.5	9.25	Rough	15.23	111.6	23.8	3.4	2 x 10
S_02_04	2	10	1.5	9.25	S4S	13.87	98.93	21.39	3.4	2 x 10
R_02_05	2	12	1.5	11.25	Rough	18.48	199.3	35.04	4.1	2 x 12
S_02_05	2	12	1.5	11.25	S4S	16.87	178	31.64	4.1	2 x 12
R_03_01	3	4	2.5	3.5	Rough	9.52	10.42	5.75	2.1	3 x 4
S_03_01	3	4	2.5	3.5	S4S	8.75	8.93	5.1	2.1	3 x 4
R_03_02	3	6	2.5	5.5	Rough	14.77	38.93	13.84	3.4	3 x 6
S_03_02	3	6	2.5	5.5	S4S	13.75	34.66	12.6	3.4	3 x 6
R_03_03	3	8	2.5	7.25	Rough	19.36	87.74	23.8	4.4	3 x 8
S_03_03	3	8	2.5	7.25	S4S	18.12	79.39	21.9	4.4	3 x 8
R_03_04	3	10	2.5	9.25	Rough	24.61	180.2	38.45	5.6	3 x 10
S_03_04	3	10	2.5	9.25	S4S	23.12	164.9	35.65	5.6	3 x 10
R_03_05	3	12	2.5	11.25	Rough	29.86	322	56.61	6.8	3 x 12
S_03_05	3	12	2.5	11.25	S4S	28.12	296.6	52.73	6.8	3 x 12
R_04_01	4	4	3.5	3.5	Rough	13.14	14.39	7.94	3	4 x 4
S_04_01	4	4	3.5	3.5	S4S	12.25	12.5	7.15	3	4 x 4
R_04_02	4	6	3.5	5.5	Rough	20.39	53.76	19.12	4.7	4 x 6
S_04_02	4	6	3.5	5.5	S4S	19.25	48.35	17.65	4.7	4 x 6
R_04_03	4	8	3.5	7.25	Rough	26.73	121.2	32.86	6.2	4 x 8
S_04_03	4	8	3.5	7.25	S4S	25.38	111.1	30.66	6.2	4 x 8
R_04_04	4	10	3.5	9.25	Rough	33.98	248.9	53.1	7.9	4 x 10
S_04_04	4	10	3.5	9.25	S4S	32.38	230.8	49.91	7.9	4 x 10

Figure 3.6. Example Lumber Properties Used in the Revit-API

During the design process, minor inputs from the user are required. For example, when designing the joists, the user has to: 1) pre-determine which condition is known, joist size or spacing of support, 2) select lumber grade and species, and 3) consider other site or loading conditions associated with adjustment factors that are applied to the tabulated design values. It should be noted that the timber formwork system designed by the proposed application is based on allowable stress design (ASD) methods with adjusted design values.

After the initial design is completed, safety checks are then performed to confirm whether the bearing stresses between components are sufficient and whether the initial design complies with the safety rules (Table 3.1). The system will also provide bracing information (e.g., horizontal construction loads along edges of the formwork) for designers to consider when planning for slab formwork bracing. The user will have a chance to preview the design before he/she confirms the design. If the design satisfies the user's need, then the formwork design can be modeled in the existing 3D BIM model.

As for designing formwork for concrete walls, after the user selects a wall, the wall information retrieved by the system consists of wall height, wall thickness, wall length, and wall geometry location in terms of the center of the selected wall. With minor input from the user, the proposed Revit-API helps the user go through a step-by-step approach to determine the size and the spacing of wall form components, including sheathing panels, studs, wales, and ties, perform bearing and safety checks, and provide wall bracing information that could be used during the planning phase.

3.7.2 Design Automation

3.7.2.1 3D Parametric Model Generation

According to Autodesk University (2019), in Revit, there are two main kinds of families: the system family and the component/loadable family. System families consist of basic predefined physical model components, such as walls, floors, and ceilings, and families related to project and system settings, such as levels, grids, sheets, and viewpoints (Autodesk, 2021b). There are limited functions that Revit users can do with the system families, as the system families cannot be created, modified, copied, or deleted. On the contrary, Revit users can create, delete, and modify the component/loadable families – they are fully customizable by the user. Therefore, by generating models in the component/loadable families, the user can create customized models, establish the relationship between family components by using parameters, load the generated family to a new project, and nest the existing family within other families to create a new family (Autodesk, 2021a).

Therefore, to generate the applicable and workable formwork systems that can be incorporated with the formwork design process, all elements of the timber slab and wall formwork systems were modeled separately and saved as Revit component families. The modeled components include sheathing panels, joists, stringers, shores, studs, and wales. For each individual form component, the family creation process followed the recommended procedures in Autodesk University (2019), as listed below.

1) Sketch the family and take notes about the family requirements (e.g., parameters, constraints, etc.),
2) Create a new family file by choosing an appropriate family template or using an existing family file,
3) Generate family reference planes, create parameters, assign or constrain parameters to reference planes,
4) Create object geometry and lock it to the reference plans,
5) Save the created family and test it in a project.

When creating families for form components, family parameters were created to control the properties of the generated models, including length, width, and height. In Revit, the family parameters can be saved as either instance or type parameters. The primary difference between these two types is whether the parameters can be editable on an element-by-element basis. For instance parameters, changing the values of one instance would not affect the other instances in the current or future projects. However, the changes to type parameters on one instance would have impacts on all other instances of the same type in the current or future projects (Autodesk University, 2019). In the created families, the main type of parameters generated is labeled dimension. The labeled dimensions are used to control the individual sizes of the modeled form components, and they could be varied in the same or different models. Therefore, all of the labeled dimensions were saved as instance parameters under the dimension group with a data format in length.

After all the individual components were successfully modeled as Revit component families, the next step was to integrate the component families to form a single slab/wall formwork system. The newly integrated family could be viewed as a host family. By linking the corresponding parameters between the nested families and the host family, the behavior of the nested and the host families could be updated together. Figure 3.7 displays the integrated slab formwork family and the associated family parameters. As shown in the figure, besides the parameters related to the sizes of form components, some values in the slab formwork family, such as the number of joists in two directions (denoted as Number_of_Joist_UD and Number_of_Joist_LR), are determined by formulas. The use of mathematical equations in parameters is to relate the number of form components to variable dimensions in the model and to control the modeled formwork geometry.

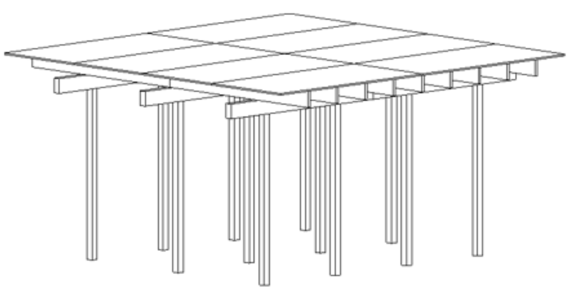
3.7.2.2 Formwork Design Automation

The use of external events connects the created 3D parametric models for slab and wall formwork systems with the design procedures (an external asynchronous process apart from the model) and enables the automation in modeling the designed formwork in the proposed Revit-API. As stated in Autodesk (2018), the framework of the external events accommodates the use of modeless dialogs that do not require the user’s response before continuing the program. Use of external events is suitable for the formwork design automation purpose, because once the design values are determined and confirmed by the user, there is no further response required from the user to complete the modeling process – it can be achieved automatically through the use of external events.

The generation of external events in the proposed Revit-API follows the guidance provided in Autodesk (2018), and examples provided in online posts on the topic (The

Building Coder, 2013; 2015; Revit API Forum, 2019). In general, the use of the external events framework should follow the steps below (Autodesk, 2018):

1) Implement an external event handler by deriving from the IExternalEventHanlder interface;
2) Create an ExternalEvent using the static ExternalEvent.Create() method;
3) When an event occurs in the modeless dialog where a Revit action needs to be taken, call ExternalEvent.Raise();
4) Revit will call the implementation of the IExternalEventHandler.Execute() method when there is an available Idling time cycle.



Family Types

Type name: Standard

Search parameters

Parameter	Value	Formula
Constraints		
Default Elevation	0' 0"	=
Dimensions		
Elevation_SlabBottom_Ground (default)	8' 4"	=
Joist_Actual_b (default)	0' 1 1/2"	=
Joist_Actual_d (default)	0' 8"	=
Joist_Length (default)	8' 0"	=
Joist_Offset_Bottom (default)	0' 0"	= ((Number_of_Joist_UD * Joist_Length) - (Slab_Width + Sheathing_Offset_Up + Sheathing_Offset_Bottom)) / 2
Joist_Spacing (default)	1' 7 51/256"	=
Sheathing_l_Length (default)	8' 0"	=
Sheathing_Thickness (default)	0' 0 3/4"	=
Sheathing_Offset_Bottom (default)	0' 6"	= Sheathing_Offset_Up
Sheathing_Offset_Left (default)	0' 6"	= Sheathing_Offset_Right
Sheathing_Offset_Right (default)	0' 6"	= (Number_of_Sheathing_LR * Sheathing_l_Length - Slab_Length) / 2
Sheathing_Offset_Up (default)	0' 6"	= (Number_of_Sheathing_UD * Sheathing_l_Width - Slab_Width) / 2
Sheathing_l_Width (default)	4' 0"	=
Shore_Actual_b (default)	0' 3 1/2"	=
Shore_Actual_d (default)	0' 3 1/2"	=
Shore_Length (default)	7' 0"	= Elevation_SlabBottom_Ground - Sheathing_Thickness - Joist_Actual_d - Stringer_Actual_d
Shore_Offset_Left (default)	2' 0"	= ((Slab_Length + Sheathing_Offset_Left + Sheathing_Offset_Right) - (Number_of_Shore_LR - 1) * Shore_Spacing_LR) / 2
Shore_Spacing_LR (default)	4' 0"	=
Slab_Length (default)	15' 0"	=
Slab_Thickness (default)	0' 8"	=
Slab_Width (default)	15' 0"	=
Stringer_Actual_b	0' 3 1/2"	=
Stringer_Actual_d (default)	0' 7 1/4"	=
Stringer_Length (default)	8' 0"	=
Stringer_Offset_Bottom (default)	3' 0"	= ((Slab_Width + Sheathing_Offset_Up + Sheathing_Offset_Bottom) - ((Number_of_Stringer_UD - 1) * Stringer_Spacing_UD)) / 2
Stringer_Offset_Left (default)	0' 0"	= ((Number_of_Stringer_LR * Stringer_Length) - (Slab_Length + Sheathing_Offset_Left + Sheathing_Offset_Right)) / 2
Stringer_Spacing_UD (default)	5' 0"	=
Other		
Number_of_Joist_LR (default)	9	= (Slab_Length + Sheathing_Offset_Left + Sheathing_Offset_Right) / Joist_Spacing - 1
Number_of_Joist_UD (default)	2	= (Slab_Width + Sheathing_Offset_Up + Sheathing_Offset_Bottom) / Joist_Length
Number_of_Sheathing_LR (default)	2	= roundup(Slab_Length / Sheathing_l_Length)
Number_of_Sheathing_UD (default)	4	= roundup(Slab_Width / Sheathing_l_Width)
Number_of_Shore_LR (default)	4	= roundup((Slab_Length + Sheathing_Offset_Left + Sheathing_Offset_Right) / Shore_Spacing_LR)
Number_of_Shore_UD (default)	3	= Number_of_Stringer_UD
Number_of_Stringer_LR (default)	2	= roundup((Slab_Length + Sheathing_Offset_Left + Sheathing_Offset_Right) / Stringer_Length)
Number_of_Stringer_UD (default)	3	= roundup(Slab_Width / Stringer_Spacing_UD)
Identity Data		

Figure 3.7. Slab Formwork Family and Family Parameters

In the first step, the purpose of creating of an external event handler is to register a class of the external event with Revit. So that when the corresponding external event is raised by the program (in step 3), the Execute method is invoked. The second step is to create an external event that handles the model automation process. The process consists of three main steps: 1) load the created formwork family, 2) place a family instance at the geometric location of the selected wall/slab, and 3) change the instance parameters based on the formwork values obtained from the design procedures. Figure 3.8 shows the example code used to place a slab family instance and change the corresponding parameters based on the design values.

```
using (Transaction t = new Transaction(doc))
{
    t.Start("Place a family instance");
    XYZ mypoint = center;
    StructuralType st = StructuralType.NonStructural;

    if (!symbol_slabformwork.IsActive)
    {
        symbol_slabformwork.Activate();
        doc.Regenerate();
    }
    PlaceSlabFormwork = doc.Create.NewFamilyInstance(mypoint, symbol_slabformwork, st);
    t.Commit();
}

using (Transaction changeparameter = new Transaction(doc))
{
    changeparameter.Start("Change formwork parameters");
    PlaceSlabFormwork.LookupParameter("Slab_Width").Set(ResultVariable.SlabWidth_ft);
    PlaceSlabFormwork.LookupParameter("Slab_Length").Set(ResultVariable.SlabLength_ft);
    PlaceSlabFormwork.LookupParameter("Slab_Thickness").Set(ResultVariable.SlabThickness_in / 12);
    PlaceSlabFormwork.LookupParameter("Elevation_SlabBottom_Ground").Set(ResultVariable.SlabHeight_ft);

    PlaceSlabFormwork.LookupParameter("Sheathing_Thickness").Set(DataConversion.ConvertFractionToDouble(ResultVariable.S_Tab2_SheathingThickness_User_in) / 12);
    PlaceSlabFormwork.LookupParameter("Joist_Spacing").Set(ResultVariable.S_Tab2_JoistSpacing_User_in / 12);

    PlaceSlabFormwork.LookupParameter("Joist_Actual_b").Set(FormworkCalculation.ConvertNominalToStandard(ResultVariable.S_Tab3_Joist_b_nomi_User_in) / 12);
    PlaceSlabFormwork.LookupParameter("Joist_Actual_d").Set(FormworkCalculation.ConvertNominalToStandard(ResultVariable.S_Tab3_Joist_d_nomi_User_in) / 12);
    PlaceSlabFormwork.LookupParameter("Stringer_Spacing_UD").Set(ResultVariable.S_Tab3_StringerSpacing_User_in / 12);


    PlaceSlabFormwork.LookupParameter("Stringer_Actual_b").Set(FormworkCalculation.ConvertNominalToStandard(ResultVariable.S_Tab4_Stringer_b_nomi_User_in) / 12);
    PlaceSlabFormwork.LookupParameter("Stringer_Actual_d").Set(FormworkCalculation.ConvertNominalToStandard(ResultVariable.S_Tab4_Stringer_d_nomi_User_in) / 12);
    PlaceSlabFormwork.LookupParameter("Shore_Spacing_LR").Set(ResultVariable.S_Tab4_ShoreSpacing_User_in / 12);

    PlaceSlabFormwork.LookupParameter("Shore_Actual_b").Set(FormworkCalculation.ConvertNominalToStandard(ResultVariable.S_Tab5_Shore_b_nomi_User_in) / 12);
    PlaceSlabFormwork.LookupParameter("Shore_Actual_d").Set(FormworkCalculation.ConvertNominalToStandard(ResultVariable.S_Tab5_Shore_d_nomi_User_in) / 12);

    changeparameter.Commit();
}
```

Figure 3.8. Example Code to Place a Family Instance and to Change Parameters Based on the Slab Formwork Design

The third step is to raise the modeless dialog (the external event created in step 2) within the proposed Revit-API. Therefore, when the ExternalEvent.raise() method is called by the user who attempts to generate the formwork model in Revit after completing the formwork design process, Revit will call the IExternalEventHanlder.Execute() method (created in step 1), and execute the external event (created in step 2) to complete the transactions to load the created family, place a family instance, and update the parameters of the instance.

3.7.3 Revit-API Formwork Design and Model Application

As a result, the proposed Revit-API integrates the formwork design and model generation processes described above. This section introduces the main functions, and presents the workflow of the proposed Revit-API formwork design and model application.

To open the proposed application to design forms for concrete walls or slabs, the first step is to click on the button on the ribbon bar in Revit (Figure 3.9). Then, the system displays a pop-up welcome message to the user that reads "Please select an elevated concrete slab or a concrete wall to continue…" (Figure 3.10).

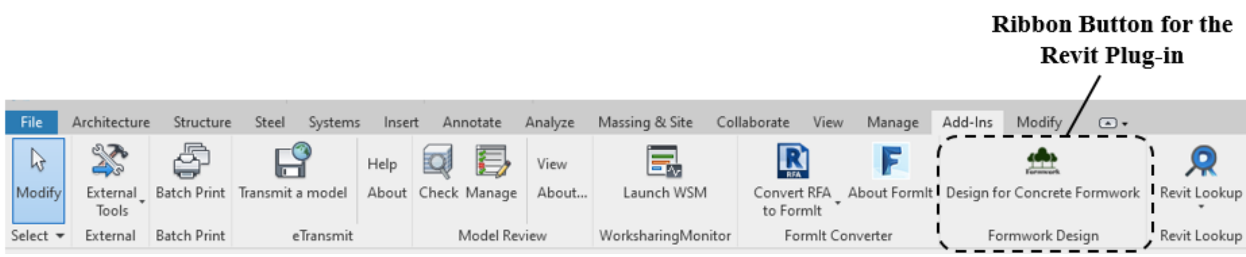


Figure 3.9. Open the Proposed Revit-API by Clicking the Ribbon Button

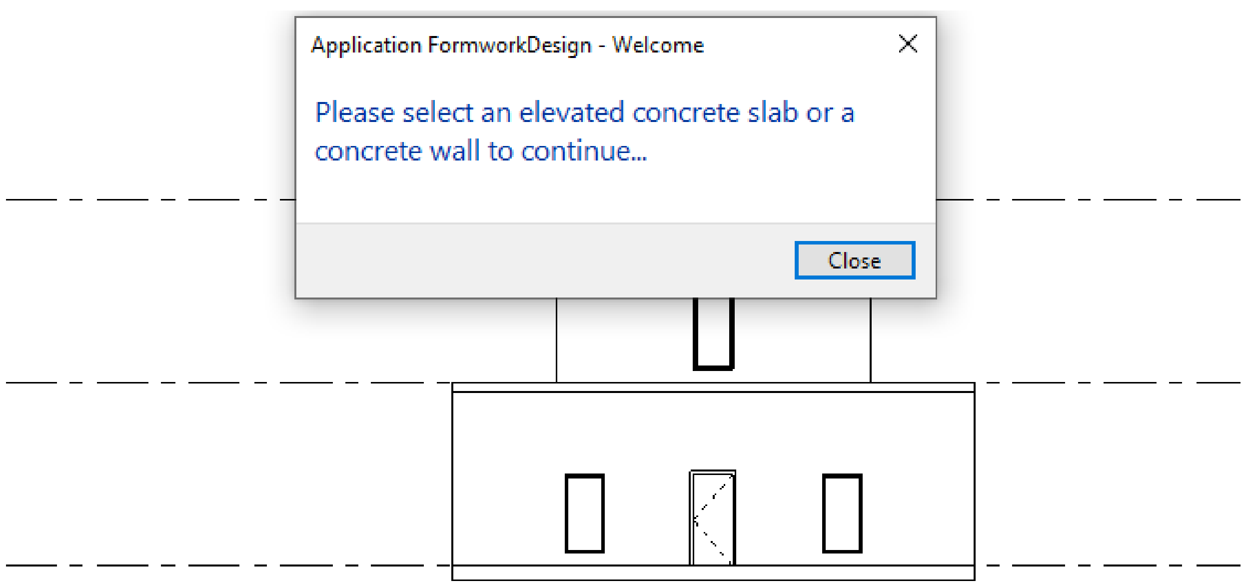


Figure 3.10. Welcome Message of the Proposed Revit-API

After the user makes a selection of a wall or a slab in the existing 3D BIM model (in Figure 3.11, a wall), a window form appears to extract (by clicking "Yes") and show basic information (e.g., wall/slab thickness, length, width) for the selected item. If the retrieved information is incorrect or the user wants to make adjustment(s), the user could enter the identified data manually. Once the information is verified and/or input by the user, in the next step, the main form with control tabs (Figure 3.12) is shown to guide the user through the step-by-step design procedures.

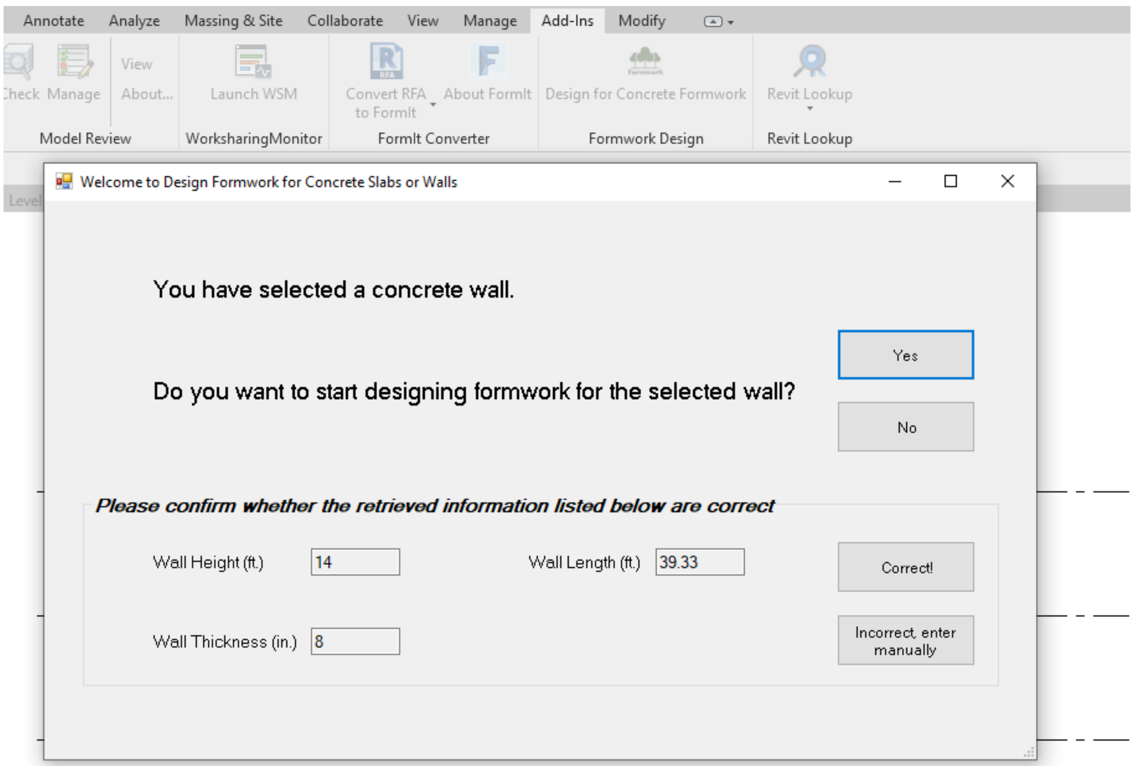


Figure 3.11. Formwork Design Information Extracted by the Proposed Revit-API

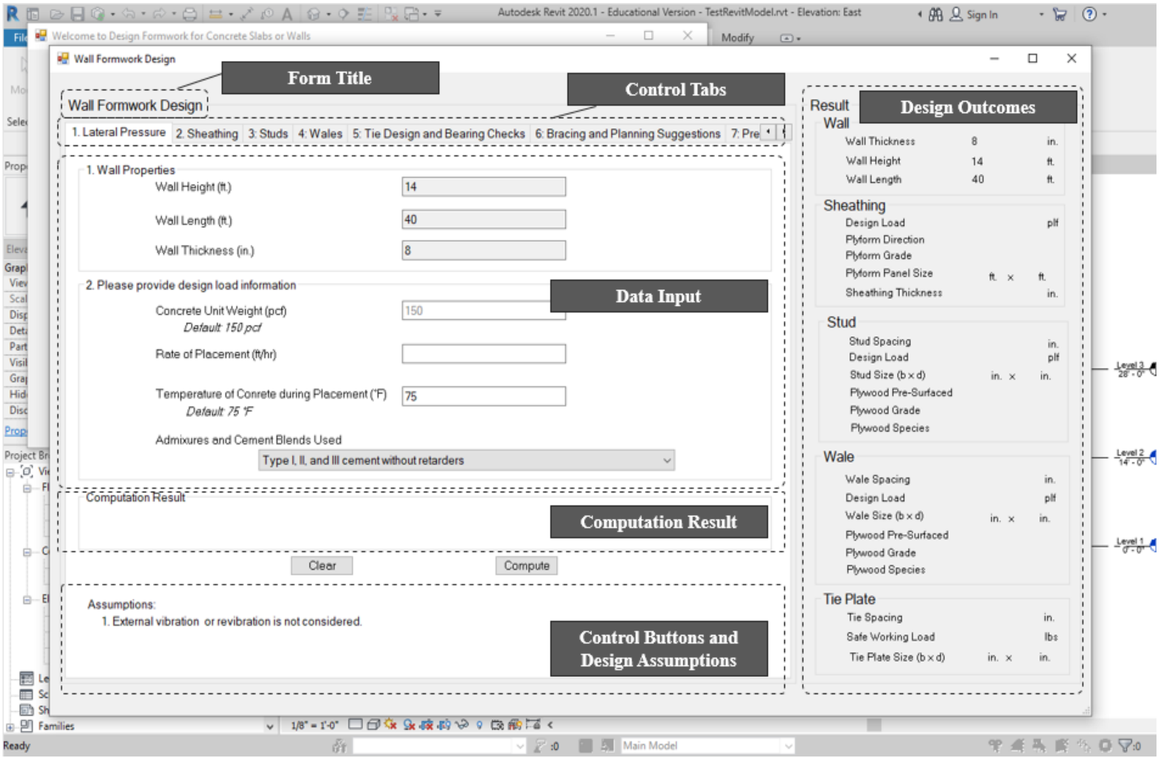


Figure 3.12. User Interface of the Main Form of the Proposed Revit-API

The main form provides a set of tools that are designed for the user to navigate and run the design process, as well as areas to display design outcomes. The main form consists of the following features.

- Form Title: shows whether the form displayed is for wall formwork design or slab formwork design.
- Control Tabs: provides guidance on the design procedures of formwork systems, and enables users to switch among different design tasks. In the current version, the tabs included in the current version for slab and wall formwork design are listed in Table 3.2.
- Data Input: allows users to select applicable design conditions from drop-down lists or manually enter the required information.
- Computation Result: provides recommended design values for users to consider.

- Control Buttons and Design Assumptions: provides buttons to reset data input, conduct analysis, confirm a design decision, and model design features, and displays assumptions used in the design process.
- Design Outcomes: presents user's design decisions for formwork components.

Table 3.2. Control Tabs in the Revit-API for Slab and Wall Formwork Design

Tab #	Slab Formwork Design	Wall Formwork Design
1	Design Load	Lateral Pressure
2	Sheathing	Sheathing
3	Joists	Studs
4	Stringers	Wales
5	Shores	Tie Design and Bearing Checks
6	Bearing Checks	Bracing and Planning Suggestions
7	Bracing and Planning Suggestions	Preview and Model
8	Preview and Model	

As shown in Table 3.2, the design procedure form has a total of eight tabs for slab formwork design, including tabs for the: 1) Design load, 2) Sheathing, 3) Joists, 4) Stringers, 5) Shores, 6) Bearing checks, 7) Bracing and Planning Suggestions, and 8) Preview and Model. For wall formwork design, there are seven tabs: 1) Lateral pressure, 2) Sheathing, 3) Studs, 4) Wales, 5) Tie Design and Bearing Checks, 6) Bracing and Planning Suggestions, and 7) Preview and Model.

In a typical design interface, the user selects applicable conditions from the drop-down lists or manually enters the required information for the plug-in to run in the data input section. As a result, the recommended design value generated by the system through a set of computations will show in the computation result section for the user to consider. Once the user confirms the design decisions based on material availability and design preferences, the design decisions will be shown on the right side of the interface, in the design outcomes section. In the process, for safety purposes, the system will pop up message boxes to inform the user whether the requirements for lateral support are met to permit using the beam stability factor (CL) equal to 1, when the ratio of depth to thickness of the selected lumber component is more than 2 to 1.

After the initial design of the basic formwork components is decided, bearing checks are conducted, i.e., whether allowable bearing stresses exceed the actual bearing stresses. For instance, for slab formwork, the bearing stress checks include the bearing stresses between the joists and stringers and between the stringers and shores. And for wall formwork, the bearing stress checks include the bearing stresses between the studs and wales and between wales and ties. In addition to the bearing checks, for slab formwork, a formwork weight check will be performed to confirm whether the estimated formwork weight is larger than the actual formwork weight.

The next step is to continue the design for bracing in the tab “Bracing and Planning Suggestions”. In the current version, the bracing design only supports determining the design load for slab and wall formwork bracing. For health and safety purposes, the API provides the function to check whether an individual form component exceeds the maximum load for manual lifting to prevent the development of MSDs in form workers. For slab formwork, the system will also provide fall protection reminders for designers/planners if the selected slab is evaluated to 6 feet or more above the lower level/ground.

After the design process is completed and the design is verified by the user, the user can preview the design (Figure 3.13). If the design is satisfactory, the user can then click the button “Model Formwork in Revit” to model the designed components in Revit. Figure 3.14 displays an example of the modeled wall formwork in the existing 3D BIM model.

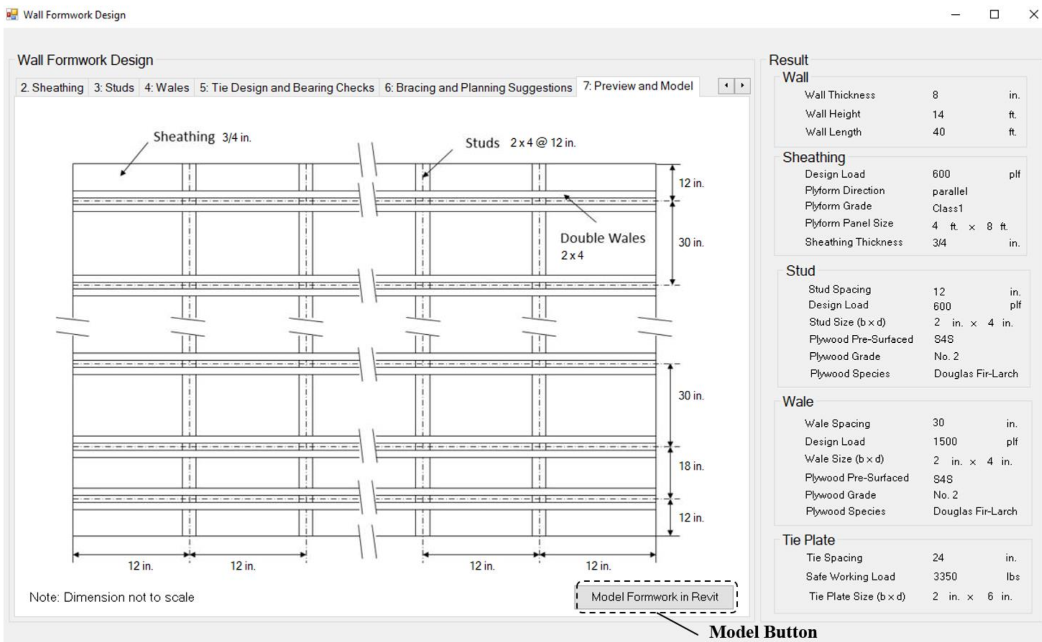


Figure 3.13. Preview the Formwork Design in the Proposed Revit-API

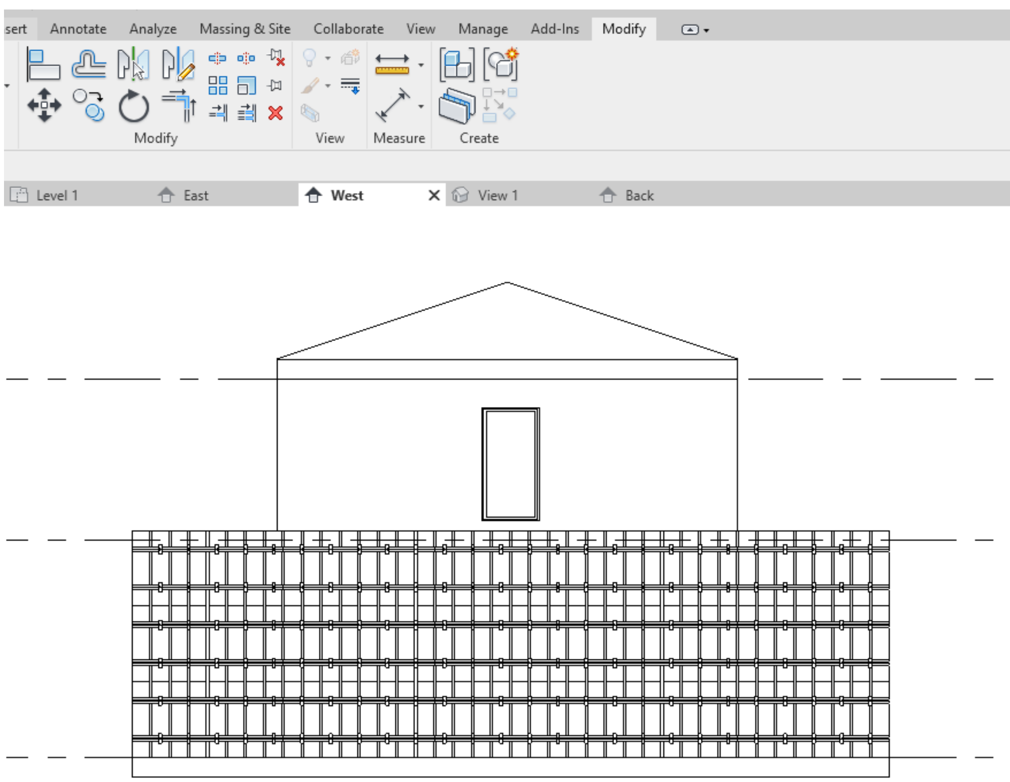


Figure 3.14. Modeled Formwork in Revit

3.8 Case Study

A 3D model of a simple two-story building was created in Revit. Then, the proposed Revit-API was tested on an elevated, flat rectangular-shaped, normal-weight concrete slab (8 in. thick), and a normal-weight concrete wall (8 in. thick, 40 ft. wide, and 14 ft. tall) from the model to demonstrate the design process and verify its applicability. Moreover, to confirm the correctness of the proposed Revit-API, two formwork design examples (Example 7.4 for slab form design and Example 7.2 for wall form design in ACI Formwork for Concrete (ACI, 2014a)) served as the ground truth.

Similar design assumptions are used in the case study for the two demonstrated examples. Only minor adjustments to the design assumptions from the original examples (e.g., ceiling height, sheathing panel size, etc.) are made so that the two examples could be demonstrated within the same Revit model. For the slab form design (Example 7.4), the design assumptions include the followings:

- 8 in. thick, normal-weight concrete slab;
- Ceiling height is 14 ft.;
- ¾-in Structural I, B-B Plyform sheathing (4 ft. x 8 ft. panels);
- Construction grade, Douglas Fir-Larch, S4S framing members;
- Span length for stringer and shoring will be 5 ft.;
- The estimated weight of forms is 8 psf;
- Forms will be substantially reused (no adjustment needed for short-term load);
- Job conditions are such that the wood joists and stringers will not be subject to wet service;
- Deflection of framing members is limited to 1/360 times the span length.

As shown in Figure 3.15, after initiating the developed plug-in in Revit and going through the step-by-step design procedures according to the abovementioned design assumptions, the form design for the selected concrete slab is complete. The design result (shown on the right side of Figure 3.15) is consistent with that in Example 7.4 provided by ACI (2014a). However, it is worth mentioning that the design values generated in the process might be slightly different from what is shown in the ACI example. To be conservative, the proposed API considers construction live load when computing vertical deflection, which is different from the design process contained in the ACI book (ACI, 2014a). Once the user confirms the design and is ready to model the designed form in Revit to update the original 3D BIM model, the designed slab form model would be generated automatically (Figure 3.16) after the user clicks the button "Model Formwork in Revit" on the proposed Revit-API user interface (Figure 3.15). In Figure 3.16, only the modeled slab form is visible – all the other 3D elements are made invisible to differentiate the generated form model.

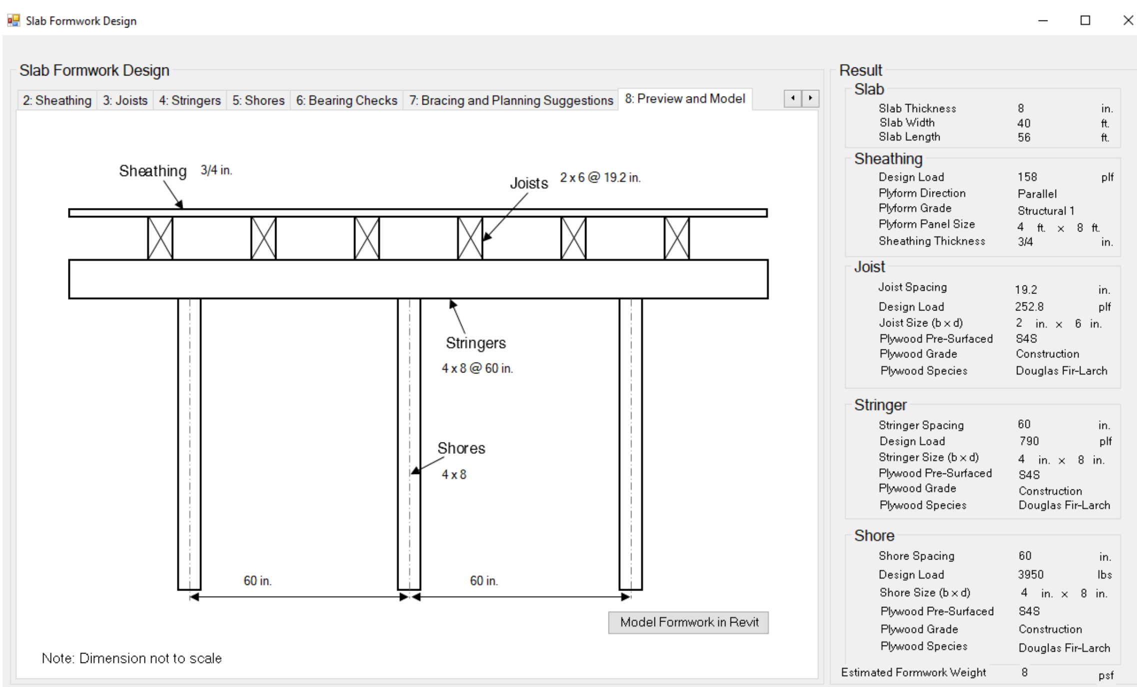


Figure 3.15. Slab Formwork Design Example Result

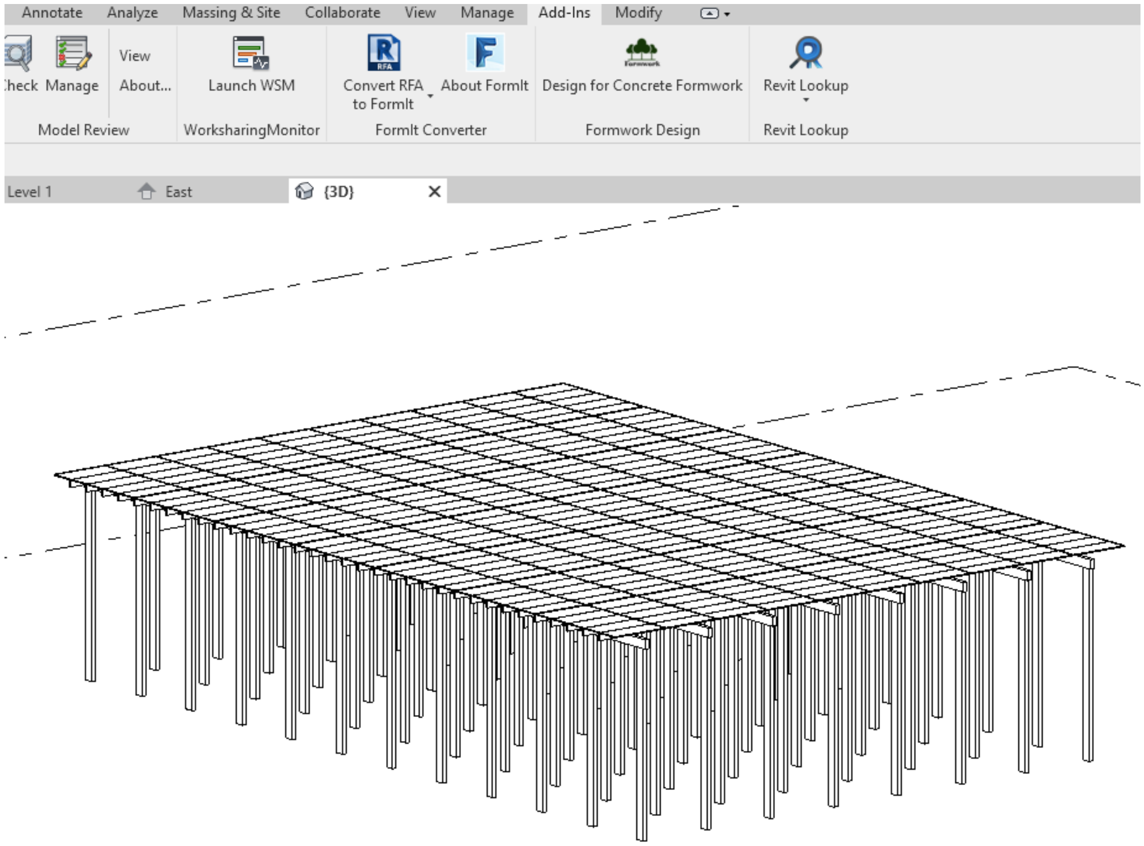


Figure 3.16. Designed Slab Formwork in Revit

As for the wall form design (Example 7.2), the case study contains the following design assumptions:

- Normal-weight (with Type II cement, no pozzolans or set-retarding admixtures) concrete wall;
- Concrete will be placed at a rate of 3ft/hr, and internally vibrated;
- Temperature of concrete at placement: 60°F;
- Class I, B-B Plyform sheathing (4 ft. x 8 ft. panels), face grain: horizontal;
- No 2. grade, Douglas Fir-Larch, S4S framing members;
- 2 x 4s for studs and wales;
- 3350 lb (safe working load) ties;
- 2 x 6 in. wedge plates;
- Short-term load duration adjustments will apply to forms;

- Deflection of framing members (sheathing and studs) is limited to the lesser of 1/360 times the span length or 1/16 in.

Similarly, once the user goes through the systematic design procedures based on the abovementioned design assumptions for the selected wall, in the last tab of the proposed API, the users can view the end result of the design (Figure 3.17), and model the designed wall form in Revit (Figure 3.18). In Figure 3.18, Revit model elements, such as walls, doors, windows, floors, are made invisible to show the modeled wall form clearly. By comparing the design result with Example 7.2 in the ACI book, the correctness of the proposed Revit-API for wall formwork design is confirmed. Additionally, upon preliminary tests by the author, compared to obtaining the design values manually (e.g., calculating by hand and searching for design values in tables from the ACI book), the use of the proposed tool saves time – it takes less than 10 minutes to complete the original one-hour-long formwork design process, in addition to the time efficiency provided by the tool in the modeling process.

Appendix II provides detailed design procedures and results for all the proposed tabs (Table 3.2) for the two examples described in this section.

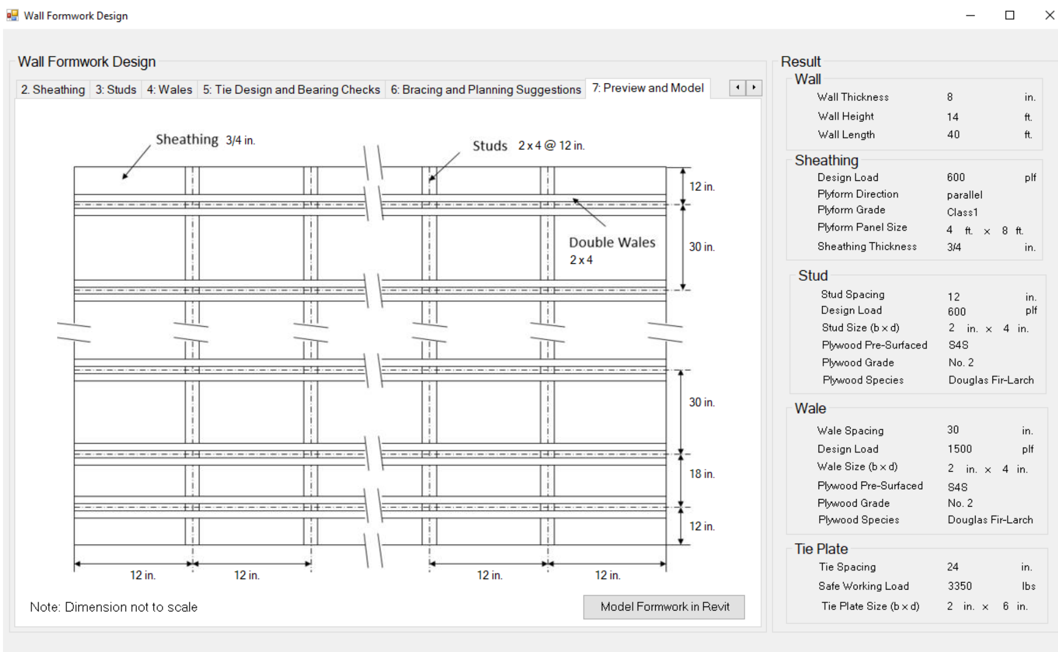


Figure 3.17. Wall Formwork Design Example Result

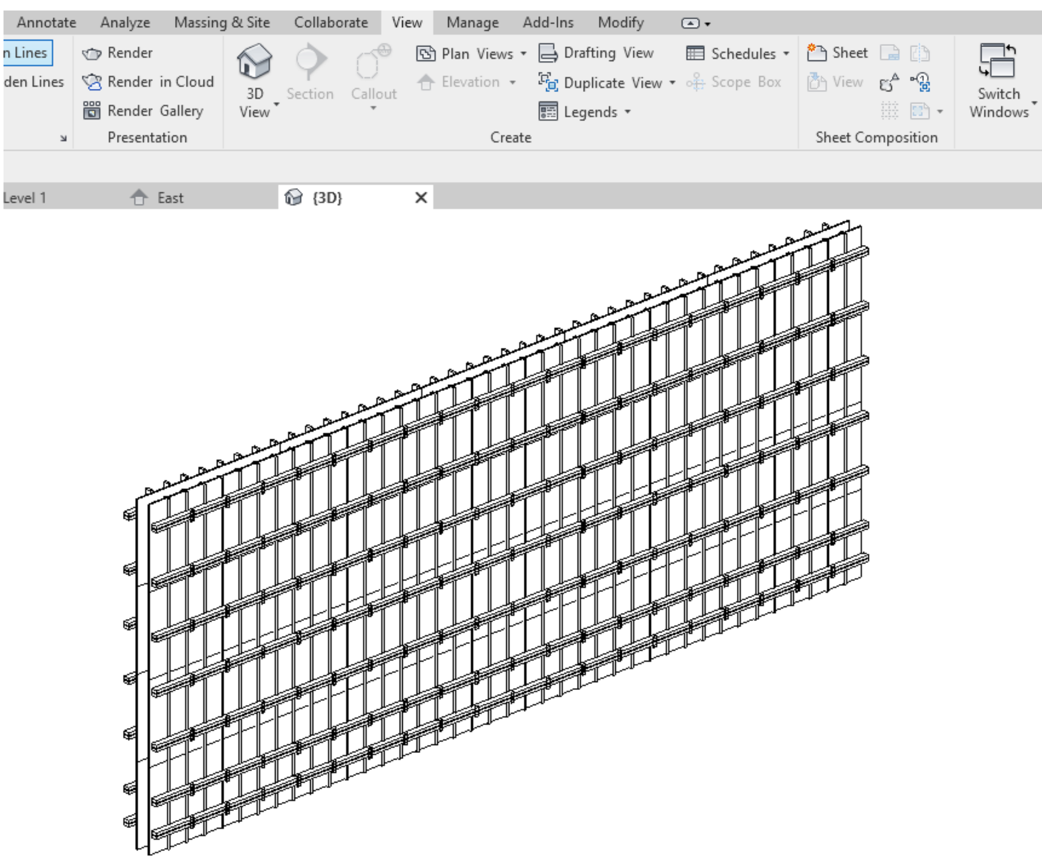


Figure 3.18. Designed Wall Formwork in Revit

3.9 Research Validation

3.9.1 Survey Development

A survey questionnaire was sent to researchers and industry practitioners who are familiar with concrete formwork and BIM to investigate the workability, effectiveness, and usefulness of the proposed Revit-API tool for formwork design and model. Building upon the survey questions used in Manuscript #1 to understand the professionals' views on adopting technologies for temporary structures, questions that are relevant to the proposed design tool (Part 2 in Appendix I) were added to the original survey. Revisions were made to the original IRB documents, and the researchers obtained approval from the IRB Office at the authors' institution.

The survey questions that directly related to the present study (Manuscript #2) consist of two parts. The first part asked if the participants took part in the previous study their opinions about applying technologies on temporary structures (the focus of Manuscript #1), and solicited their background information about their experiences with temporary structures, type of company in which they are employed, job title, etc. The second part of the questionnaire consisted of questions related to their experience with BIM related software, their ratings of the proposed Revit-API for formwork design and model in terms of the usefulness, effectiveness and efficiency on 5-point Likert scales, and any opinions they may have about the research in an open-ended question.

Because the developed Revit-API was still in its development stage, which was not readily available for testing on other computers except for the author's, allowing survey participants, who were not physically located at the same geographical location, to use the developed tool was infeasible. Instead, to help the participants obtain a comprehensive understanding of the research idea and the workflow of the proposed Revit-API in an efficient and intuitive manner, a YouTube video (https://youtu.be/_Jo2fg5ghEg) and a shared description document (https://drive.google.com/file/d/1wmWVL8dnu6SIR1YdmlvXswiEHHggtyr_/view?usp=sharing) were created and attached to the survey. The YouTube video and the document provided detailed descriptions about the main features contained in the proposed tool, including the research objective, the highlights of the proposed tool, the user interfaces, and the pilot applications on the two examples as described in the previous section.

3.9.2 Sampling Method

Similar to Manuscript #1, a contact list of the target population (professionals who have extensive knowledge about concrete formwork design and BIM authoring tools) is not readily available. Therefore, a similar data collection approach was used - purposive/judgmental sampling was the primary sampling method, which is a non-probability sampling technique that does not involve random selection. Additionally, some participants helped with survey distribution by forwarding the study invitation to other professionals who might be interested in the study. Participants reached in this way are considered as samples that were collected through snowball sampling technique, and are also not randomly selected from the target population. As a result, selection bias occurred due to the adopted sampling techniques.

The survey was distributed to the members of ACI Committee 347 and the ASCE Construction Institute Temporary Structures Committee, scholars who have conducted research studies related to concrete formwork design and BIM, along with professionals on the authors' contact list. The total number of surveys distributed is unknown because of the use of the snowball sampling technique.

3.9.3 Survey Results

As a result, 32 responses were received, and 25 were considered valid (responses with a completion rate of 95% or above, and without indication of systematic response patterns). All the participating respondents indicated that they are familiar with concrete formwork and/or shoring. The majority of the participants (76%) have more than 10 years of industry experience, and nearly half of them (48%) have more than 20 years of experience. As for the types of companies they worked for, more than half (56%) of the participants work for either general contractor or subcontractor firms, followed by 28% who work for structural engineering firms. The remaining participants were from academia, formwork manufacturer/suppliers, and formwork consulting firms. Out of the 25 responses, seven of the responses were from project engineers, three were from project managers, and the remaining responses (15) were from chief engineers or other management personnel, such as formwork managers, directors of engineering, engineering department managers, general managers, vice presidents and presidents. With respect to the participant's personal experience using with BIM-related software or applications, more than 70 percent of the participants (76%) said "yes" that they do have experience using BM-related software or applications. The abovementioned participants' qualifications indicate that the participants have considerable experience and knowledge about the study subject, which further ensures a high level of quality and confidence in the survey results.

To investigate the usefulness and effectiveness of the proposed formwork design tool, and its potential to improve worker health and safety, the participants were invited to rate several statements on a scale of 1 to 5, where 1 indicates they strongly disagree and 5 indicates they strongly agree with the statements. A summary of the results is reported in Table 3.3. Since the average ratings for all the statements are above 3, the results reveal that the participants held generally positive perceptions of the proposed formwork design and model tool.

Among all the statements, the two statements related to time efficiency with the design and modeling aspects of the proposed tool, "the plug-in saves time when modeling formwork components" and "the plug-in saves time when designing formwork components", received the highest average rating (average rating = 4.05) and the third highest average rating (average rating = 3.83), respectively. The result suggests that the proposed tool provides an efficient way to design and model slab and wall formwork components. The second highest average rating goes to the statement "the plug-in is easy to use and implement" (average rating = 4.04, SD = 0.79), which further confirms the usability of the proposed tool.

Table 3.3. Summary Statistics of Professionals' Ratings for the Proposed Revit-API

Statement	**n**	**Rating** (1 = Strongly disagree, 5 = strongly agree)			
		Average	**Standard Deviation**	**Minimum**	**Maximum**
The plug-in is easy to use and implement.	24	4.04	0.79	2	5
The plug-in provides adequate accuracy.	24	3.50	1.00	1	5
The plug-in saves time when designing formwork components.	24	3.83	1.18	1	5
The plug-in saves time when modeling formwork components.	24	4.05	1.06	1	5
The plug-in is a labor-saving tool when designing and modeling formwork systems.	25	3.60	1.13	1	5
The plug-in has potential to improve design and model quality.	25	3.68	1.22	1	5
The plug-in has potential to improve worker health and safety.	25	3.44	1.20	1	5

However, compared to other statements, participants were relatively conservative about the potential for the plug-in to improve worker health and safety (average rating = 3.44, SD = 1.20) and the provided accuracy of the proposed design tool (average rating = 3.50, SD = 1.00). The comments and suggestions submitted by the participants provided additional insights into the ratings and the tool in general. Many respondents expressed concerns regarding the user of the proposed design tool. One major concern was whether the end-user is a qualified person for the work. For example, one participant commented that, "I have a general fear of tools like this being used by underqualified personnel to do design work. I think it's a valuable tool for modeling, but on the design side in the wrong hand it could be bad for safety and quality." Another two respondents also expressed their concerns that use of the proposed tool may make the design and construction of temporary structures less safe, as "this takes the engineer out of the design process. They (engineers) will assume that the program has done its job, and they will not spend the time looking at the complex areas where the failures usually happen," and in high-risk project conditions "(the use of the tool may) cause a false security with the design/details".

Some comments were related to the application area of the proposed tool. Formwork manufacturers, such as PERI and DOKA, have developed their own formwork design and planning applications for projects that use their prefabricated or modular form products that are made of steel or aluminum. Nowadays, for large projects, especially for concrete slabs, contractors tend to use pre-engineered metallic formwork systems rather than timber systems. Therefore, the proposed tool is suitable for conditions that are more favorable to timber formwork systems, such as small contractors and projects with small concrete slabs and/or only a few concrete walls, for which using pre-engineered metallic formwork systems is not economically viable. Additionally, a few participants mentioned that they prefer a standalone version, thereby removing the restriction from the Autodesk Revit platform.

Apart from the abovementioned comments, many participants provided several constructive suggestions for areas of improvement of the proposed tool. For example, the current version of the tool only supports the basic features of regular-shaped timber formwork designs, it does not support irregular-shaped walls or slabs, non-typical details, and cantilever forms. Other suggestions included giving greater consideration to formwork constructability (e.g., having consistent and equal wale spacing in the design, industry utilization of shore clamps for timber shoring posts to adjust shore height, etc.) and connections between form members, providing corresponding code references in the design process, enabling a data export feature for spot checks of the calculations, providing quantity takeoffs of the designed components, and listing the limitations of the proposed tool within the software.

3.10 Discussion

Concrete formwork systems are an essential element to ensure the success of concrete construction. The design and planning of concrete formwork influences the cost, productivity, and quality of the entire project, as well as worker safety and health

(Ratay, 2004; Tam et al., 2005; KimTaehoon et al., 2012). To improve the quality and efficiency of formwork design and planning, a number of studies have attempted to develop tools with the help of BIM-based software. The focused areas of the developed tools vary. Some studies explored how to incorporate the systematic and complex formwork design process with the existing BIM models, through API (Singh et al., 2016; Singh et al., 2017), Ruby code (Hyun et al., 2018), or Dynamo (Romanovskyi et al., 2019). Some developed tools focused on providing additional features to assist formwork planning, including material quantity take-off (Singh et al., 2016; Singh et al., 2017; Hyun et al., 2018; Khosakitchalert et al., 2019; Lee et al., 2021), cost analysis (Hyun et al., 2018), and constructability analysis (Kannan and Santhi, 2013). Table 3.4 presents comparisons of the proposed BIM-based formwork design and modeling tool and the existing BIM-based tools. Compared to other tools, the developed BIM-based tool integrates the formwork design process, generates typical formwork system models, and automates the modeling process through a streamlined approach. It also takes worker safety and health into consideration.

The workability, usefulness and effectiveness of the proposed tool was verified by formwork design professionals who work in academia and industry. Even though the nonrandom sampling methods and the relatively small sample size (n = 25) limit the generalizability of the study findings, given the considerable knowledge and experience that the majority of the survey participants have with formwork (more than 70% of the participants have more than 10 years of industry experience), the proposed tool was found to be easy to use and implement, time efficient when designing and modeling formwork components, and have the potential to improve design and model quality.

However, based on the professionals' feedback and the comparisons to the other formwork tools, the proposed tool is subject to several limitations. Formwork design can be very complex for concrete components with irregular shapes. Unfortunately, the current version of the proposed tool only supports a single rectangular-shaped concrete slab/wall. Additionally, formwork details and accessories including diagonal bracing, anchors, and hangers, all of which are common to formwork designers, are not considered in the current version. As for the formwork material, the proposed tool only provides a limited lumber options to select, which does not support the use of prefabricated or modular formwork systems. Moreover, features to support formwork planning, such as material quantity take-off, cost analysis, and constructability analysis are not readily available.

Additionally, based on information retrieved from existing BIM models, the approach used in this manuscript that integrates design processes, safety and health considerations, and model automation through API in the BIM authoring tools, could also be applied to design and model permanent structures. For example, with some modifications, the tool could be used to partially design permanent wood-framed floor and walls in buildings. The tool could also be used to design formwork for other types of structures than buildings, such as bridge projects.

Table 3.4. Comparisons of the Proposed Tool and the Existing BIM-Based Formwork Tools

Authors (Year)	**Platform**	**Material**	**Function**						
			Design process integration	**BIM Models of form components**	**Formwork modeling automation**	**Quantity takeoff**	**Cost analysis**	**Construct-ability analysis**	**Safety and health consideration**
Kannan and Santhi (2013)	Revit	Not mentioned		✓				✓	
Singh et al. (2016; 2017)	Revit	Wood	✓			✓			
Hyun et al. (2018)	Revit	Wood	✓			✓	✓		
Khosakitchalert et al. (2019)	Revit	Not mentioned				✓			
Romanovskyi et al. (2019)	Revit	Wood and metal	✓						
Lee et al. (2021)	Unity3D and Blender3D	Metal		✓	✓	✓			
The proposed tool	Revit	Wood	✓	✓	✓				✓

3.11 Conclusions and Future Work

The present study proposes a framework to incorporate the concrete formwork design process and safety rules with BIM authoring tools for designers when designing and planning temporary structures. A Revit plug-in aimed at utilizing the existing data from BIM models to design and model timber slab/wall formwork systems was developed. The developed tool provides a streamlined and integrated approach to conduct formwork design, which expands the BIM design and model capabilities. Applying the proposed plug-in on a case study with a 3D BIM model of a two-story concrete-framed building demonstrates the interfaces and workability of the tool. The workability, usefulness, and efficiency of the proposed tool was also verified by formwork professionals using a survey questionnaire. It is anticipated that combing the expertise from the end user and the benefits provided by the developed tool will allow both designers and contractors to select appropriate formwork members and assess the design in an efficient manner without tedious structural analysis efforts.

It is worth noting that the proposed tool is designed to aid the development of formwork design. The end user must be a qualified formwork designer. He/she should consider project- or site-specific conditions, and use his/her best judgment when using the tool – the design information provided by the proposed tool is for general informational purposes only.

However, there are some limitations associated with the current study and future research could be conducted to improve the tool and to address the limitations. Future work could be performed to support irregular-shaped concrete slabs/walls and use prefabricated and modular formwork components with more design details (e.g., anchors, hangers, corner forms, cantilever forms, etc.). Built upon the proposed tool, future work could be conducted to facilitate the planning process. Tasks may include incorporating BIM formwork designs with a work breakdown structure (WBS) and schedules for site planning including planning for form reuse, performing shoring/reshoring analysis, detailed quantity take-offs, cost estimates, and constructability analysis. With the development of such tools, the visual presentations and simulations of formwork designs and planning will also ensure effective communication and collaboration among stakeholders. The use of the formwork model and the simulation of the construction process could also be used to train workers on the safe operating procedures to erect and strip formwork.

4. MANUSCRIPT #3 – SELECTION AND APPLICATION OF TECHNOLOGIES FOR MONITORING FORMWORK DURING CONCRETE PLACEMENT

The content of Chapter 4 is an adapted and extended version of the following conference paper:

> Jin, Z. and Gambatese, J.A. (2020). "A Fuzzy Multi-criteria Decision Approach to Technology Selection for Concrete Formwork Monitoring." *Proceedings of the 2020 Construction Research Congress*, ASCE, Tempe, AZ, March 8-10, 2020.

Based on the research findings described in Chapter 2 (Manuscript #1), the use of technologies on temporary structures was generally supported by industry professionals. The current design and inspection approaches are associated with many deficiencies such as design errors, inadequate formwork inspection quality and accuracy – more attention should be given to temporary structures. It was identified that BIM/VDC, sensor-based technology, and video/photo logs were promising to address the identified deficiencies within the current design and inspection practices and to improve the overall safety performance of temporary structures. Chapter 3 (Manuscript #2) presents a study that attempted to improve the design and model quality of concrete formwork, a type of temporary structure, as well as to improve worker safety and health using BIM authoring tools during the design and planning phases of a project. Chapter 4 (Manuscript #3) places a focus on the construction phase for the same type of temporary structure – concrete formwork.

Building upon the participants' views on the level of importance of technology selection criteria for the task of temporary structure monitoring (obtained in Manuscript #1), Manuscript #3 aims to select an appropriate technology among technology alternatives through a decision-making analysis for formwork monitoring during concrete placement, which is when most formwork failures occur. Based on the selection result, a formwork monitoring tool can be developed to address the inadequacies in the current inspection and monitoring practices identified in

Manuscript #1, including low frequency and accuracy, as well as high-level interruptions to the construction operations, and to improve worker and inspector safety.

4.1 Abstract

The design and construction of formwork systems used to construct concrete elements have contributed to a significant portion of injuries and fatalities. Past investigations of such tragedies have shown that concrete formwork often exposes construction workers to a high level of safety risk during concrete pouring and formwork removal. Given that advanced technologies have been successfully applied to monitor the structural health of permanent structures, the potential use of technologies to improve the performance of concrete formwork during operations is promising. However, technology selection is typically one of the most difficult tasks for decision-makers as it is often a multi-criteria decision-making (MCDM) problem that includes vagueness and uncertainty. The study presents a two-step approach to select and apply technology to improve the inspection quality of formwork during concrete placement. The study firstly adopts a systematic decision-making process based on fuzzy set theory to determine the most preferable technology for the application of concrete formwork monitoring. With such information, the study then proposes a wireless sensor network (WSN) concrete formwork monitoring system and tests the system on a case study project. The study demonstrates the decision-making process that involves MCDM problems with vague evaluation information by using the fuzzy analytical hierarchy process for technology selection. The rational decision-making process enables stakeholders to make an informed decision regarding technology selection. The effectiveness of data acquisition using the developed monitoring system based on the result of the technology selection process was confirmed in the case study project.

4.2 Introduction

Concrete formwork systems are a typical type of temporary structure that serve as molds and supporting members to help form and cure concrete structures. A significant number of failures of structural components within a concrete formwork system could lead to the progressive collapse of the whole temporary structure system (Buitrago et al., 2018), and cause occupational injuries and fatalities, as shown in Table 1.2. In a failure investigation study, Hadipriono and Wang (1987) surveyed 85 major formwork failures on bridge and building projects in the US. The researchers found inadequate monitoring procedures was one of the major problems that facilitated the occurrence of formwork failures, which is in line with the findings from other researchers, such as Lew (1984), André et al. (2012), and Sheehan and Corley (2013). Moreover, Hadipriono and Wang (1987) reported that approximately half of all the surveyed collapses occurred during concrete placement. Considerable lateral pressure may be generated due to an excessive rate of pouring and the use of powered equipment, i.e., formwork vibrators for compaction of concrete.

Current practices related to inspection and monitoring concrete formwork mainly rely on periodic inspections and observations by competent inspectors to confirm whether the structures and the operations are in accordance with construction plans, regulations, and guidance (Feng and Dai, 2014; Beale and André, 2017). The results are obtained either through visual-based assessments (Cheng et al., 2009; Jung, 2014) or instrument-based surveying (Hope and Chuaqui, 2007; Moon et al., 2011; Feng et al., 2015b). Manual practice involving human effort is time-consuming and prone to human error (Xie and Wang, 2009; Hwang and Liu, 2010; Jung, 2014), and may not provide accurate and timely warning of possible form displacement or potential failures. Thus, a more effective way to monitor concrete formwork systems is warranted.

With the development of construction technologies, several sensor-based and vision-based technologies, such as laser scanning and wireless sensors, have shown promising results in tracking workers, resources, and materials in the entire life cycle of building projects (Cheng and Teizer, 2013; Li et al., 2016). In addition to the purpose of construction process management, an extension to the applications of such technologies is structural health monitoring (SHM) for permanent structures (Li et al., 2004; Park et al., 2007a). Such technologies may have the potential for application at small (size) and temporary (short-term) scales, such as for concrete formwork.

However, selecting from a list of possible technologies for concrete formwork monitoring is challenging.

The present study formulates the technology selection problem for monitoring the performance of concrete formwork as an MCDM problem and proposes to solve it based on fuzzy set theory. Based on the selection result, the study proposes a real-time WSN formwork monitoring system that could be used to collect data on the structural behavior of concrete formwork components during concrete placement to assess structural integrity, in order to ensure worker and inspector safety. The study's significance lies in the rational selection process of preferences of technologies, and in the development and application of a technology solution for the task of monitoring formwork during concrete placement.

4.3 Background

4.3.1 Concrete Formwork Inspection and Monitoring

As described in Section 1.1.3.1.2, safety regulations and guidance have been developed to ensure safe operations prior to, during and after concrete placement. For instance, as per OSHA CFR 1926.703(b)(3), equipment for erecting shoring shall be inspected immediately prior to, during, and after concrete placement. In OSHA CFR 1926.703(b)(8)(i), it is also noted that the erected temporary structure shall be inspected by an engineer qualified in structural design.

More specifically, visual observations from the formwork designer's side should occur at regular intervals, as per BC 3305.3.3 and 3305.3.3 in the 2014 and 2016 NYC Building Code. At a minimum, such inspections should be conducted: 1) right after formwork-related incidents or violations are issued; and 2) when concrete construction operations are substantially modified before the execution of the change. If the observer discovers discrepancies from the original formwork design, the observer should notify the concrete contractor to correct the discrepancy. In the meantime, on-site safety managers are responsible for correcting any formwork issues that are related to site safety. Follow-up observations should be conducted by the formwork designer's side to confirm proper corrective actions have been taken (International Code Council, 2014; 2016).

From the contractor's side, formwork inspections of form components, including shores, reshores, braces, and other supports, should be performed periodically by a qualified person designated by the contractor before the placement of reinforcing steel and during the placement of concrete. The elevations, camber, and vertical alignments of formwork systems should be inspected with equipment, i.e., telltale devices including string lines and plumb lines, during and after concrete placement (International Code Council, 2014; 2016; Shamash and Frias, 2016). Telltale devices should also be installed on forms and elsewhere to give early warning signs of formwork movement during concreting. Furthermore, during concreting, it is essential to have an experienced, competent person or persons performing continuous monitoring of the formwork system be stationed in a location that is close to the forms but is also protected. The formwork watchers could use the previously installed telltale devices to monitor the movement of the elevation, camber, and plumbness of the formwork system. An early sign of formwork failures is the gradually increasing deflection in slabs and shores. Therefore, after placing all batches of concrete, the form watchers should remain on duty until telltale devices show that no more deflection is occurring (ACI, 2014a).

Obviously, current practices related to concrete formwork inspection and monitoring rely on manual efforts. Subjective judgments from formwork inspectors play significant roles in the process. The inspection and monitoring quality is highly dependent upon the experiences of the formwork inspectors. Information obtained by such labor-intensive methods is highly unreliable and ineffective for managing inspection and monitoring results (Wang, 2008). Besides, the limited presence capabilities and availabilities of the inspectors inhibit performing continuous monitoring (Cho et al., 2018). Thus, tools that provide objective measurements and continuous monitoring could overcome the abovementioned limitations.

4.3.2 Technology Applications for Inspection and Monitoring and SHM

The use of technologies provides a highly efficient and accurate approach for real-time construction safety management and facilitates its modernization and informatization (Zhang et al., 2017). Many researchers have explored technology-based tools for continuous construction safety monitoring through mobile sensing devices (Lee et al., 2009), GPS devices (Pradhananga and Teizer, 2013), RFID-enabled smartphones (Lin et al., 2013), CPS (Zhou et al., 2019), BIM and sensors (Riaz et al., 2017; Cheung et al., 2018), UWB (Carbonari et al., 2011), wearable sensing devices (Gatti et al., 2011; Cheng et al., 2013; Shen et al., 2017), and the use of multiple sensors within the IoT environment (Zhou and Ding, 2017). The areas of focus are mainly accident prevention such as falls (Lee et al., 2009), blind spots (Zhou et al., 2019), confined spaces (Riaz et al., 2014), and overhead hazards (Carbonari et al., 2011), environmental conditions monitoring (Zhou and Ding, 2017; Cheung et al., 2018), worker physiological monitoring (Gatti et al., 2011; Cheng et al., 2013; Shen et al., 2017), construction operation monitoring (Pradhananga and Teizer, 2013), inspection, and monitoring result sharing (Lin et al., 2013; Riaz et al., 2017; Xu et al., 2019). Previous studies have shown encouraging results of technology applications in providing accurate and timely information about construction workers, equipment, and the environment for proactive safety management.

Apart from the abovementioned focus areas, few studies have placed a focus on temporary structures to improve the traditional manual inspection and monitoring practices, as previously described in Section 1.1.3.1.2. For instance, the integration of RFID and a virtual 3D model was used to verify the positions of formwork components after they were erected (Atherinis et al., 2018). Sensors including ultrasonic sensors, strain gauges, inclinometers, and load cells were used to acquire information about formwork during concrete placement to prevent structural failures (Moon et al., 2011; 2015; 2017). Subsequently, targeted on scaffolding, Yuan et al. (2014; 2016) proposed a CPM system that uses a similar set of sensors for real-time monitoring with the integration of a virtual model. The study performed by Cho et al. (2018) presents a wireless sensor solution with strain sensors for the same purpose – real-time monitoring of scaffolding. In their study, machine learning algorithms were also adopted to analyze the structural condition of a scaffold using the data collected by the sensors. Moreover, several attempts at using images or videos to detect possible temporary structure failures were made in previous studies (Feng and Dai, 2014; Jung, 2014; Feng et al., 2015b; Jung et al., 2019). However, some of the approaches did not consider the complex conditions of construction sites, only laboratory experiments were conducted (Yuan et al., 2014; 2016; Cho et al., 2018). Another drawback is that many approaches, especially vision-based approaches, were still in the exploratory phase, and they were quite limited because significant manual efforts were required to extract the required information for the monitoring purpose. Besides, many of the researchers did not use commercially available or open-source hardware or software for easy adoption and implementation by practitioners. Lastly, the use of technologies on temporary structures in these approaches did not go through a rational comparison and selection process involving the considerations of technology selection criteria and preferences of practitioners.

Furthermore, the technologies that are used on permanent structures for detecting structural displacements may also be applicable for monitoring the performance of temporary structures since temporary structures could be viewed as the “end products” of temporary work and they are used until they are no longer needed. As for concrete formwork, the formwork systems will not be stripped until the supported concrete has attained adequate strength. Various technologies have been applied to assess the displacement and deformation of structural members, and could be viewed as promising technology alternatives to be applied on temporary structure monitoring, such as sensors (Park et al., 2005; Liu et al., 2017), cameras (Park et al., 2015; Khuc and Catbas, 2017), GPS (Lovse et al., 1995; Breuer et al., 2002; Kaloop and Li, 2014), and laser scanning (Park et al., 2007; Lee and Park, 2011; Kaloop and Li, 2014).

Given the existence of several technologies that could be applicable for application to concrete formwork monitoring, to develop an effective method for the task, it is critical to select a proper technology. Selection and evaluation from multiple technology options based on a set of decision-making criteria is not easy.

4.3.3 Technology Selection Methods

Multiple measurements and methods, such as net present value (NPV), return on investment (ROI), analytic hierarchy process (AHP), and value of investing in time compression technologies, have been developed to make appropriate decisions for various applications (Chan et al., 2000; Kengpol and O'Brien, 2001). When making decisions using the abovementioned approaches, one obstacle is that the methods rely on whether assessment information is available and accurate enough. However, when making decisions, subjective judgments in terms of linguistic scales are often used to describe one or more specific assessment criteria. To make the best assessment without vagueness, Zadeh (1965) firstly introduced the concept of fuzzy set theory. Since then, the concept has been widely adopted to solve MCDM problems with incomplete and imprecise information, as it is suitable for uncertain or approximate reasoning that involves human judgments (Baloi and Price, 2003). Compared to a deterministic approach, the use of fuzzy set theory enables taking into account the uncertainty in human behavior during the decision-making process (Mesa et al., 2017). Fuzzy set theory has been applied to select technology alternatives in various applications, such as for cloud computing technology selection (Kengpol and O'Brien, 2001), photovoltaic technology selection (van de Kaa et al., 2014), and sustainable energy technology selection (Buyukozkan and Guleryuz, 2016).

In the construction industry, decision-makers often find it difficult to select the right technology for a target application without economic and functional loss. The fuzzy MCDM is identified as an appropriate way for technology selection problems (Ibadov and Rosłon, 2015), and it has been applied to select a proper technology for construction management, such as for construction materials tracking with wireless technologies (Jiang et al., 2012).

4.4 Research Objectives

The goal of this research to develop an easy-to-use technology solution for monitoring concrete formwork during placement. The specific objectives of the present study to attain the research goal are to:

(1) Select an appropriate technology from technology alternatives to monitor concrete formwork through decision-making analysis;
(2) Propose a monitoring solution for concrete formwork monitoring based on the selected technology and test it on a case study project to confirm its usefulness and effectiveness.

The proposed monitoring method is expected to overcome the limitations posed by the traditional manual-based concrete formwork inspection and monitoring practices by providing continuous and objective measurements for better safety control. The method is also expected to address the shortcomings of the existing technology-based approaches by using commercially available and open-source hardware and software for easy implementation and adoption for construction practitioners.

4.5 Research Methods

4.5.1 Research Flowchart

The present research was conducted in two phases (as shown in Figure 4.1). Phase I emphasizes selecting the best alternative among many potential technologies for concrete formwork monitoring during placement. In Phase II, the study focused on developing a technology solution based on the selection result from Phase I and applying it for the task of monitoring the performance of formwork during concrete placement.

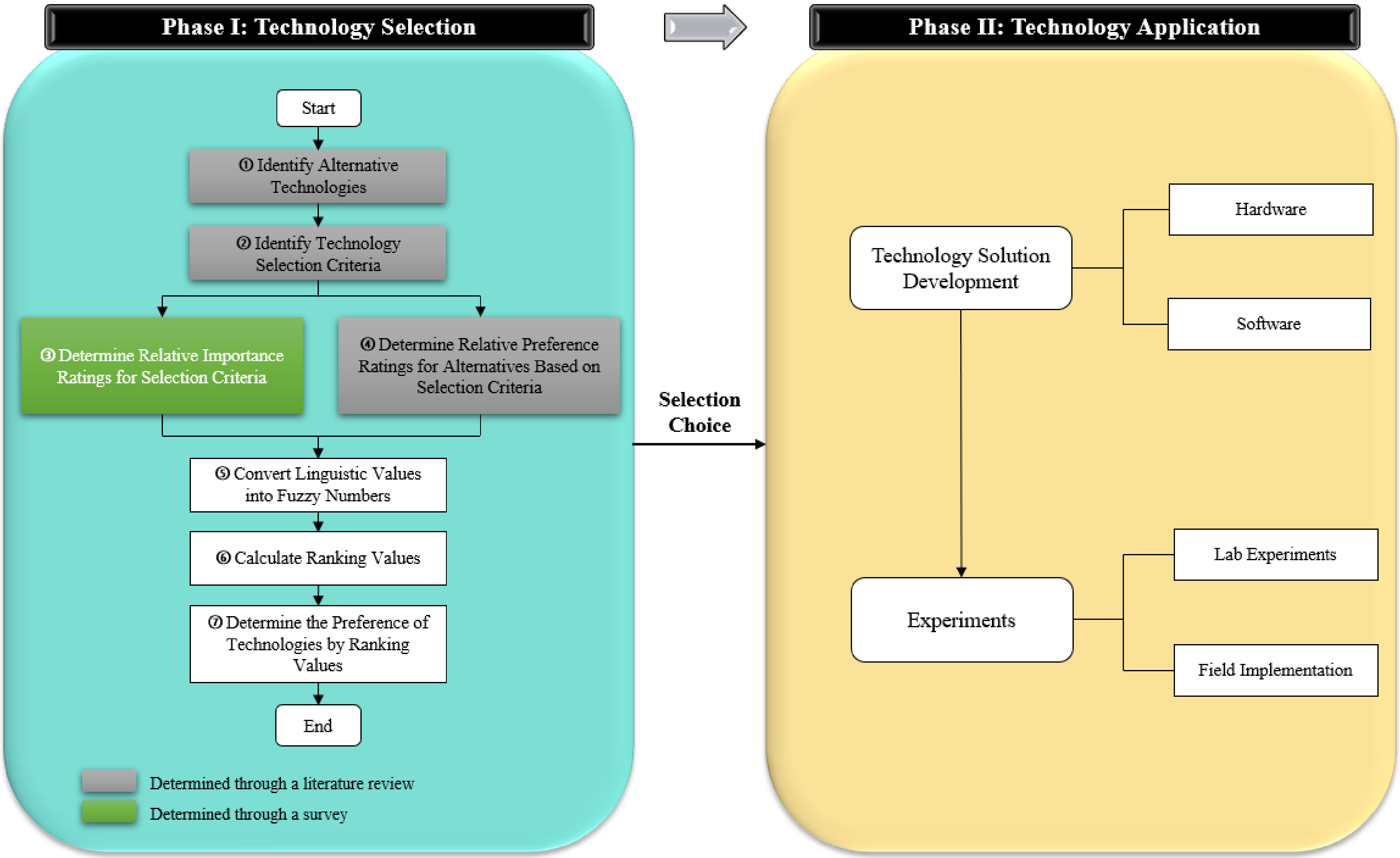


Figure 4.1. Research Flowchart for Technology Selection, Development, and Application

4.5.2 Phase I – Technology Selection

As presented in Figure 4.1(left), the technology selection flowchart describes a hypothetical case scenario in which a construction field manager attempts to select an appropriate technology available in the market for concrete formwork monitoring during placement. It also highlights the technology selection process with the implementation of a fuzzy AHP approach. The fuzzy AHP method was developed from the traditional AHP; it handles vagueness and uncertainty in decision-making through the fuzzy set theory developed by Zadeh (1965). The method is a useful analysis tool for assessing the relative importance of criteria and ranking alternatives. The research steps are adapted from the study performed by Chan et al. (2000), and are as follows:

- Step 1: Alterative technology identification;
- Step 2: Technology selection criteria identification;
- Step 3: Determination of relative importance ratings for selection criteria;
- Step 4: Determination of relative preference ratings for technology alternatives based on selection criteria;
- Step 5: Convert linguistic values into fuzzy numbers;
- Step 6: Computation of ranking values;
- Step 7: Determination of technology preference.

The identification of technology alternatives (Step 1) and technology selection criteria (Step 2), as well as the determination of relative preference ratings for technology alternatives (Step 4) were achieved through a literature review. The determination of relative importance ratings for selection criteria (Step 3) was performed through a survey question that seeks temporary structure professionals' opinions on the importance of technology selection criteria. The details about the survey can be found in Sections 2.5 and 2.6. After the two relative ratings were determined, the next step (Step 5) was to convert linguistic values into fuzzy numbers. Fuzzy numbers, which are derived from membership functions, are used to describe different scales for a linguistic variable. The present study adopts the commonly used triangular fuzzy numbers, and follows the analysis process presented by Ayhan (2013) to obtain the ranking scores using the geometric mean technique (Step 6). The alternative with the highest score is the most preferable one (Step 7).

4.5.3 Phase II – Technology Application

Based on the selection result obtained from Phase I, in Phase II (Figure 4.1(right)), a monitoring system was developed to acquire required formwork assessment information during concrete placement. In the process, appropriate hardware components were selected and configured, and codes were developed to obtain the specific parameters pertaining to the monitoring task. Next, lab experiments were conducted to test the proposed monitoring system. Finally, the proposed system was applied to a real-world project during concrete placement to verify its effectiveness and to investigate potential challenges to its application.

4.6 Phase I – Technology Selection: Hypothetical Case Decision-Making

This section presents the detailed step-by-step analysis process using the proposed flowchart (Figure 4.1 (left)) to solve the hypothetical case MCDM problem.

4.6.1 Alternative Technologies Identification

Potential types of technologies that could be applied to concrete formwork monitoring were identified (Table 4.1) through a literature review. As mentioned previously, for concrete formwork inspection and monitoring, the most important task is to assess the extent of form displacement in order to provide early warning of potential structural failures. Therefore, the identified technologies include those that have been applied to SHM of permanent structures in terms of assessing structural displacement or have been examined in previous temporary structures monitoring research.

Table 4.1. Identified Types of Technology Alternatives for Formwork Monitoring

Potential Technologies	References
A1. Sensor networks	Ko and Ni (2005), Lynch (2006), Moon et al. (2011; 2017), Yuan et al. (2014; 2016)
A2. Laser scanning	Park et al. (2007), Yang et al. (2014) ,Yang et al. (2018)
A3. Vision-based (photos/videos)	Park et al. (2010), Feng et al., (2015a; 2015b), Yoon et al. (2018),Wang et al. (2018)

4.6.2 Technology Selection Criteria Identification

Factors that affect technology selection were identified previously (Manuscript #1) through a literature review based on the identified technologies and previous construction technology studies performed by Jiang et al. (2012), Ibadov and Rosłon (2015), Kopsida et al. (2015), and Nnaji et al. (2018b). As a result, ten technology selection criteria were recorded, as shown in Table 2.2, which can be grouped into four categories: performance, interface, cost, and practicability.

4.6.3 Determination of Relative Importance Ratings

Through the mixture of sampling methods in the survey (described in Section 2.5), 60 responses were received, of which 46 (77%) were used in the analysis due to inadequate completion in some of the responses. All participants indicated that they have worked with temporary structures, and 36 out of the 46 responses (78%) were received from respondents who have more than 10 years of work experience in the industry. The participants were invited to rate the importance of each identified criterion when selecting technologies for monitoring temporary structures (Table 2.2) based on a five-point Likert scale from 1 for “not at all important,” to 5 for “extremely important.” To make comparisons among selection criteria, the RII values were calculated, as shown in Table 2.4.

Since the computed RII values do not indicate the extent to which one criterion is more important than the others, the present study calculated the differences in RII, to denote the relative importance ratings on a linguistic scale composed of “strongly more important (SM),” “moderately more important (MM),” “nearly equally important

(NI)," "equally important (EI)," "moderately less important (ML)," and "strongly less important (SL)," as shown in Table 4.2.

Table 4.2. Fuzzy Conversion Scale

Triangular Fuzzy Scale	Importance Comparison		Performance Comparison
	Linguistic Expression	***Differences in RII***	***Linguistic Expression***
(3, 5, 5)	Strongly more important (SM)	(0.075, 0.15]	Strongly preferred (SP)
(1, 3, 5)	Moderately more important (MM)	(0.025, 0.075]	Moderately preferred (MP)
(1/3, 1, 3)	Nearly equally important (NI)	[-0.025,0) ∪ (0, 0.025]	Nearly equally preferred (NP)
(1, 1, 1)	Equally important (EI)	0	Equally preferred (EP)
(1/5, 1/3, 1)	Moderately less important (ML)	[-0.075, -0.025)	Moderately unpreferred (MU)
(1/5, 1/5, 1/3)	Strongly less important (SL)	[-0.15, -0.075)	Strongly unpreferred (SU)

4.6.4 Determination of Relative Preference Ratings for Technology Alternatives

Since no systematic review of the performance comparisons of the technologies used for SHM was found, the relative preference ratings for the identified alternatives were determined by reviewing papers that discuss the performance of technologies, and by utilizing the researchers' best judgment. Similar to the previous step, to describe the relative preference ratings, a linguistic scale of "strongly preferred (SP)," "moderately preferred (MP)," "nearly equally preferred (NP)," "equally preferred (EP)," "moderately unpreferred (MU)," and "strongly unpreferred (SU)" was used (Table 4.2).

4.6.5 Conversion of Linguistic Values into Fuzzy Numbers

Based on the fundamental Saaty's scale (Saaty, 1987), a triangular membership function of the linguistic scale based on the relative importance/preference (Figure 4.2), corresponding to the simplified fuzzy conversion scale (Table 4.2), was developed. The membership function of the linguistic scale used was adopted from Chan et al. (2000).

With the determined RII values from Step 3 (determination of relative importance ratings) and the conversion scale ((Table 4.2), a pairwise important comparison matrix was determined (Table 4.3). For instance, in comparison with C2 (Provides desirable results (level of accuracy, robustness, etc.)) with an RII of 0.850, C1 (Meets required needs; has required features) has a “moderately less important (ML)” RII of 0.786 (difference in RII = -0.064). Therefore, the cell a12 has a value of (1/5, 1/3, 1). Similarly, the pairwise preference comparison matrix was achieved for the potential technology alternatives A1, A2, and A3 (Table 4.4) based on the preference ratings determined from Step 4 and the conversion scale.

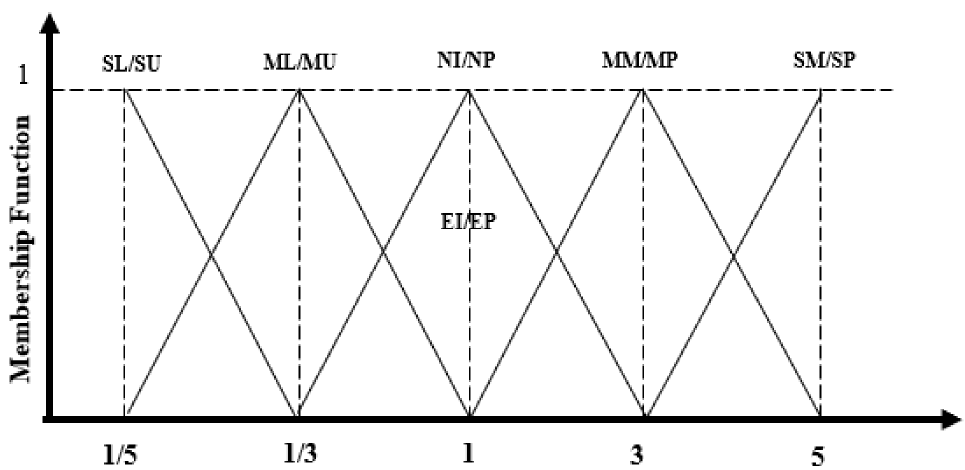


Figure 4.2. Membership Function of Linguistic Scale Based on Relative Importance / Performance Ratings

Table 4.3. Pairwise Importance Comparison Matrix

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
C1 (RII: 0.786)	(1, 1, 1)	(1/5, 1/3, 1)	(1/5, 1/3, 1)	(1/3, 1, 3)	(3, 5, 5)	(1, 3, 5)	(1/5, 1/3, 1)	(1, 3, 5)	(1/3, 1, 3)	(1/3, 1, 3)
C2 (RII: 0.850)	(1, 3, 5)	(1, 1, 1)	(1, 3, 5)	(3, 5, 5)	(3, 5, 5)	(3, 5, 5)	(1/3, 1, 3)	(3, 5, 5)	(1, 3, 5)	(1, 3, 5)
C3 (RII: 0.819)	(1, 3, 5)	(1/5, 1/3, 1)	(1, 1, 1)	(1, 3, 5)	(3, 5, 5)	(3, 5, 5)	(1/5, 1/3, 1)	(3, 5, 5)	(1, 3, 5)	(1/3, 1, 3)
C4 (RII: 0.773)	(1/3, 1, 3)	(1/5, 1/5, 1/3)	(1/5, 1/3, 1)	(1, 1, 1)	(1, 3, 5)	(1, 3, 5)	(1/5, 1/3, 1)	(1, 3, 5)	(1/3, 1, 3)	(1/3, 1, 3)
C5 (RII: 0.705)	(1/5, 1/5, 1/3)	(1/5, 1/5, 1/3)	(1/5, 1/5, 1/3)	(1/5, 1/3, 1)	(1, 1, 1)	(1/3, 1, 3)	(1/5, 1/5, 1/3)	(1/3, 1, 3)	(1/5, 1/5, 1/3)	(1/5, 1/5, 1/3)
C6 (RII: 0.718)	(1/5, 1/3, 1)	(1/5, 1/5, 1/3)	(1/5, 1/5, 1/3)	(1/5, 1/3, 1)	(1/3, 1, 3)	(1, 1, 1)	(1/5, 1/5, 1/3)	(1/3, 1, 3)	(1/5, 1/3, 1)	(1/5, 1/5, 1/3)
C7 (RII: 0.845)	(1, 3, 5)	(1/3, 1, 3)	(1, 3, 5)	(1, 3, 5)	(3, 5, 5)	(3, 5, 5)	(1, 1, 1)	(3, 5, 5)	(1, 3, 5)	(1, 3, 5)
C8 (RII: 0.727)	(1/5, 1/3, 1)	(1/5, 1/5, 1/3)	(1/5, 1/5, 1/3)	(1/5, 1/3, 1)	(1/3, 1, 3)	(1/3, 1, 3)	(1/5, 1/5, 1/3)	(1, 1, 1)	(1/5, 1/3, 1)	(1/5, 1/3, 1)
C9 (RII: 0.791)	(1/3, 1, 3)	(1/5, 1/3, 1)	(1/5, 1/3, 1)	(1/3, 1, 3)	(3, 5, 5)	(1, 3, 5)	(1/5, 1/3, 1)	(1, 3, 5)	(1, 1, 1)	(1/3, 1, 3)
C10 (RII: 0.795)	(1/3, 1, 3)	(1/5, 1/3, 1)	(1/3, 1, 3)	(1/3, 1, 3)	(3, 5, 5)	(3, 5, 5)	(1/5, 1/3, 1)	(1, 3, 5)	(1/3, 1, 3)	(1, 1, 1)

4.6.6 Computation of Ranking Values

For the pairwise importance comparison matrix (Table 4.3) and the pairwise performance comparison matrix (Table 4.4), as suggested by Buckley (1985) for a given triangular fuzzy number reciprocal matrix A = $[a_{ij}]$, the geometric row mean can be used to determine the relative weights scale. For the i^th row, the geometric row mean is determined by:

$$r_i = (a_{i1} \otimes a_{i2} \otimes a_{i3} \otimes \ldots \otimes a_{ik})^{1/k}, \qquad (1)$$

where k is the number of criteria. Then, the fuzzy weight (w_k), which is also the normalized geometric row mean, is given by:

$$w_k = r_i \otimes (r_1 \oplus r_2 \oplus r_3 \oplus \ldots \oplus r_k)^{-1}, \qquad (2)$$

where $\oplus$ and $\otimes$ represent fuzzy addition and multiplication, respectively (Chan et al., 2000). Details regarding the fuzzy arithmetic can be found in the paper by Jiang et al. (2012).

Lastly, the obtained fuzzy weights w_k need to be de-fuzzified by the center of area method and then normalized, similar to what was conducted in Ayhan (2013). By multiplying each technology selection criteria weight with the corresponding alterative weight, the scores for each technology alternative were calculated (Table 4.5).

Table 4.4. Pairwise Alternative Preference Comparison Matrix

		A1	A2	A3	References
C1. Meets required needs; has required features	**A1**	(1, 1, 1)	(1/3, 1, 3)	(1/3, 1, 3)	Lynch (2006), Park et al. (2007), Feng et al. (2015b)
	A2	(1/3, 1, 3)	(1, 1, 1)	(1/3, 1, 3)	
	A3	(1/3, 1, 3)	(1/3, 1, 3)	(1, 1, 1)	
C2. Provides desirable results (level of accuracy, robustness, etc.)	**A1**	(1, 1, 1)	(3, 5, 5)	(3, 5, 5)	Yang et al. (2014), Feng et al. (2015a), Feng et al. (2015b)
	A2	(1/5, 1/5, 1/3)	(1, 1, 1)	(1, 3, 5)	
	A3	(1/5, 1/5, 1/3)	(1/5, 1/3, 1)	(1, 1, 1)	
C3. Quality of data (reliability)	**A1**	(1, 1, 1)	(1/5, 1/3, 1)	(1/5, 1/3, 1)	Lynch (2006), Yang et al. (2018), Kopsida et al. (2015)
	A2	(1, 3, 5)	(1, 1, 1)	(1, 3, 5)	
	A3	(1, 3, 5)	(1/5, 1/3, 1)	(1, 1, 1)	
C4. Less disruption to operations	**A1**	(1, 1, 1)	(1/5, 1/5, 1/3)	(1/5, 1/5, 1/3)	Park et al. (2007), Feng and Feng (2018)
	A2	(3, 5, 5)	(1, 1, 1)	(1/3, 1, 3)	
	A3	(3, 5, 5)	(1/3, 1, 3)	(1, 1, 1)	
C5. Cost of initial purchase	**A1**	(1, 1, 1)	(3, 5, 5)	(1, 3, 5)	Olsen et al. (2010), Feng et al. (2015a), Feng et al. (2015b), Kopsida et al. (2015)
	A2	(1/5, 1/5, 1/3)	(1, 1, 1)	(1/5, 1/5, 1/3)	
	A3	(1/5, 1/3, 1)	(3, 5, 5)	(1, 1, 1)	
C6. Cost of installation and maintenance	**A1**	(1, 1, 1)	(1/5, 1/5, 1/3)	(1/5, 1/5, 1/3)	Park et al. (2007), Kopsida et al. (2015), Feng and Feng (2018)
	A2	(3, 5, 5)	(1, 1, 1)	(1, 3, 5)	
	A3	(3, 5, 5)	(1/5, 1/3, 1)	(1, 1, 1)	
C7. Easy to use and implement	**A1**	(1, 1, 1)	(1, 3, 5)	(1, 3, 5)	Feng et al. (2015a), Feng et al. (2015b), Kopsida et al. (2015), Feng and Feng (2018), Yang et al. (2018)
	A2	(1/5, 1/3, 1)	(1, 1, 1)	(1/5, 1/3, 1)	
	A3	(1/5, 1/3, 1)	(1, 3, 5)	(1, 1, 1)	
C8. Training requirements	**A1**	(1, 1, 1)	(3, 5, 5)	(3, 5, 5)	Kopsida et al. (2015)
	A2	(1/5, 1/5, 1/3)	(1, 1, 1)	(1/5, 1/3, 1)	
	A3	(1/5, 1/5, 1/3)	(1, 3, 5)	(1, 1, 1)	
C9. Time efficiency in data acquisition	**A1**	(1, 1, 1)	(3, 5, 5)	(3, 5, 5)	Kopsida et al. (2015)
	A2	(1/5, 1/5, 1/3)	(1, 1, 1)	(1/5, 1/3, 1)	
	A3	(1/5, 1/5, 1/3)	(1, 3, 5)	(1, 1, 1)	
C10. Time efficiency in data processing and interpretation	**A1**	(1, 1, 1)	(1, 3, 5)	(1, 3, 5)	Kopsida et al. (2015)
	A2	(1/5, 1/3, 1)	(1, 1, 1)	(1/3, 1, 3)	
	A3	(1/5, 1/3, 1)	(1/3, 1, 3)	(1, 1, 1)	

4.6.7 Determination Preference of Technologies

As shown in Table 4.5, Alternative 1 (sensor networks) has the highest total evaluation score based on the analysis with ten technology selection criteria and fuzzy preferences on three technology alternatives.

Table 4.5. Aggregated Results for Each Technology Alternative

Criteria		Scores of alternatives with respect to each criterion		
	Weights	**A1**	**A2**	**A3**
C1	0.095	0.333	0.333	0.333
C2	0.193	0.653	0.223	0.124
C3	0.133	0.168	0.534	0.298
C4	0.085	0.096	0.452	0.452
C5	0.029	0.582	0.097	0.322
C6	0.035	0.097	0.582	0.322
C7	0.189	0.534	0.168	0.298
C8	0.038	0.653	0.124	0.223
C9	0.095	0.653	0.124	0.223
C10	0.108	0.528	0.236	0.236
	Total	**0.453**	**0.281**	**0.266**

4.7 Phase II – Technology Application: Sensor Network Monitoring System Development and Implementation

Based on the results obtained from the hypothetical case decision-making process, the sensor network monitoring system is the most promising technology to be used for monitoring the performance of formwork during concrete placement. The development of a continuous monitoring system would have great potential to improve worker safety in the construction industry (Asadzadeh et al., 2020).

4.7.1 Proposed Real-time Formwork Monitoring System

As described in Section 4.3.1, it is essential to make sure that the contractor, and the form designer constantly monitor and inspect the formwork during concrete placement to ensure the safety of structures against collapse. Understanding the structural behavior and identifying critical locations, along with their maximum allowable limits, for signs of failure are required for the task.

According to Alamin (1999), Zhang et al. (2012), Moon et al. (2018), and Barbosa et al. (2014), formwork structural integrity is impacted by many factors, including:

- Deviations in dimensions or shapes between the used formwork components and the design, which have impacts on the properties of the material;
- Discrepancies between the actual form construction and the form design;
- Reuse of formwork, which has impacts on the reliability of form components after a number of re-uses;
- Poor foundation and soil conditions, which could lead to formwork settlements;
- Poor control and treatment of concrete flow, which may result in concentrated loads that exceed the maximum allowable limit.

For the present study, the focus is placed on whether the structural behavior of a formwork component exceeds the maximum allowable limit. Both vertical and horizontal components were considered. Hence, the study proposes a real-time formwork monitoring WSN system that continually tracks the structural deformation of formwork components. Figure 4.3 shows the architecture of the proposed wireless real-time formwork monitoring system. The proposed system is a wireless sensor network (WSN) system, which transmits data collected from a set of spatially distributed sensors to a central terminal automatically via a network to monitor physical or environmental conditions. The components of a WSN system often consist of a central processor, communication module, and sensor nodes with internal or external power supplies (Zhang et al., 2017; Frei et al., 2020).

The proposed system consists of two primary sensor nodes that work independently. One (sensor node 1) measures and collects the data regarding the distance between a sheathing panel and the ground/lower level to check the displacement of a horizontal component. The other one measures and collects the data regarding the amount of deflection of a shoring post, a vertical component. Each sensor node is a combination of sensors, a microcontroller, a Wi-Fi module, and an SD card module. Therefore, each sensor node serves as a data collection center, as well as a wireless sensor node. After the two sensor nodes are configurated and installed on a construction site, the real-time data are sent to a web service via the internet automatically. The user (e.g., formwork designer, superintendent, project manager, construction safety manager, etc.) can then track the real-time information regarding the formwork during concrete placement using his/her desktop computer, laptop computer, or phone, thus achieving long-term monitoring. The proposed application is not only a WSN system, it is also an IoT-based application on construction projects. It makes use of sensors for continuous monitoring over the Internet to prevent accidents.

The data sampling rate obtained by the web service is mainly restricted by the sampling rate of the sensors themselves, the speed of the Wi-Fi hotspot used, and the default sampling rate setting by the developer. Therefore, in addition to the Wi-Fi module, an SD card module is also included in each sensor node to back up the sensor readings. The stored data in the SD cards is also used for further analysis.

4.7.1.1 Framework for the Proposed Real-Time Formwork Monitoring System

Constructing a wireless sensor network system requires selection, configuration and integration of many hardware and software components (Ferdoush and Li, 2014). Figure 4.4 presents the development framework of the proposed real-time formwork monitoring system. It consists of three main stages: 1) initiation, 2) execution, and 3) monitoring. In the first stage (initiation), hardware and software systems were selected, configured and developed to acquire the needed data for the monitoring purpose. An IoT analytics platform called Thingspeak.com was used to collect and visualize the data collected by the proposed sensor nodes through the Internet. In the second stage (execution), sensor nodes were tested and their performance was evaluated during the lab experiments. The collected data from the lab experiments were then used to select an appropriate sensor signal processing method. Finally, the proposed system was implemented on a real construction site during concrete placement (execution). The sensors were installed/placed and connected to the Internet, and the collected data were then transmitted through the Internet to the created Thingspeak channel in real-time, and stored on SD cards for further analysis.

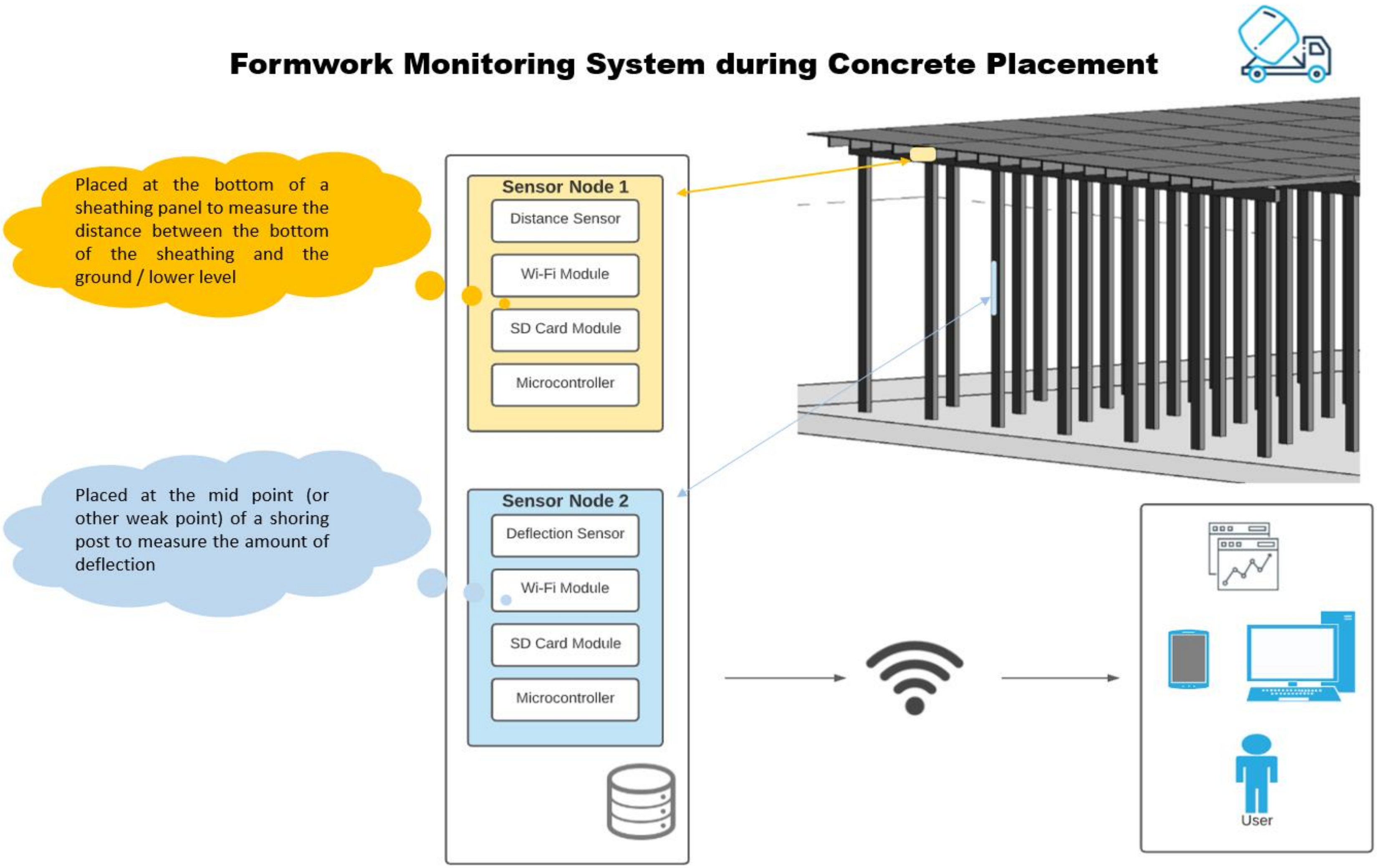


Figure 4.3. Proposed Real-Time Formwork Monitoring System

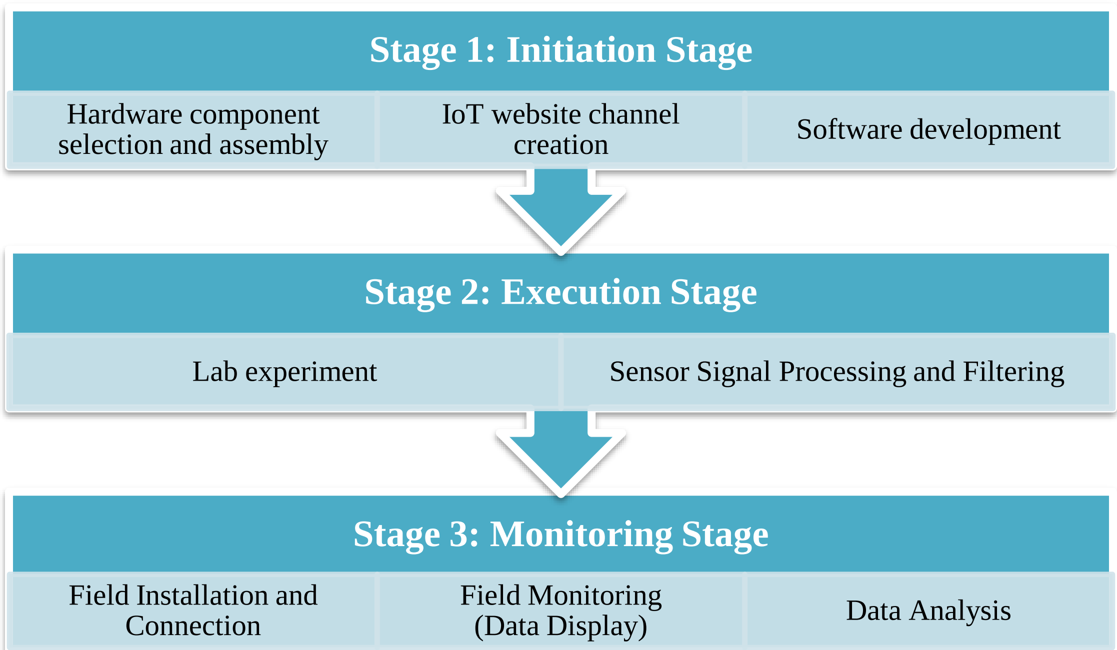


Figure 4.4. Framework for the Development of the Proposed Real-Time Formwork Monitoring System

4.7.1.2 Hardware Components

4.7.1.2.1 Microcontroller

The sensor nodes were developed using Arduino and ESP8266 Wi-Fi modules. Arduino is an open-source microcontroller development platform with easy-to-use, inexpensive and extensible hardware and software components (Arduino, 2018). The Arduino platform has been widely used in previous WSN research studies for various applications. The Arduino board used in the present study is an Arduino UNO R3. It is the most robust board and the most used and documented board of the whole Arduino family (Arduino, n.d.,). It is an ATmega328P-based microcontroller board, with a frequency of 16MHz. Because the board has six analog inputs and 14 digital input/output pins, it has the capability to work with a number of sensors at the same time. By integrating the Arduino boards with their compatible shields (also known as expansion boards) that are stackable on top of the Arduino board, it enables including extra features (i.e., data logging, LCD display, GPS logging, etc.).

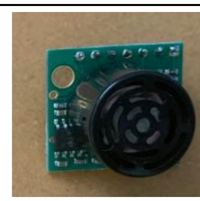
4.7.1.2.2 Sensors

- **Distance Sensor**

Ultrasonic sensors are one type of distance measurement sensor, and are low-cost, non-invasive, intrinsically safe, and capable of providing satisfactory accurate readings (Angrisani et al., 2009; Khoenkaw and Pramokchon, 2017). Ultrasonic sensors have been used in previous studies to estimate the structural behavior of temporary structure components (Moon et al., 2012; 2015; 2017). An ultrasonic sensor works by sending out a high frequency sound wave, and when the sound wave reaches the target, it bounces back to the sensor. Then the distance is measured by using the time lapse between the sending and receiving of the pulse, also known as the time of flight.

A variety of models of ultrasonic proximity sensors are available on the market, and sensor selection is often a challenging task for any system design because the selection has a significant impact on system performance (Adarsh et al., 2016). Three low-cost ultrasonic sensors were selected as promising sensors to measure the distance between the formwork components and the ground/lower level. They are an HC-SR04 (Cytron Technologies, 2013), MB1010 (MaxBotix, 2015), and MB1013 (MaxBotix, 2014). Table 4.6 presents the technical specifications and images of the three selected ultrasonic sensors. As shown in the table, sensors differ in the frequency, their sensing range, accuracy, resolution, and the operating voltage and current, which influence their capabilities in the formwork monitoring application. For instance, if formwork is elevated to an elevation above the lower level that exceeds the maximum sensing range of a sensor, then the sensor could easily fail the task as it is not able to provide readings out of its range. Since the displacement of a formwork component is often very small (e.g., several millimeters), the readings provided by the sensors need to be accurate and reliable. The selection of an appropriate ultrasonic sensor for the field experiment needs to consider the actual field condition (e.g., the elevation of the slab, and the maximum allowable limit for a structural component).

Table 4.6. Technical Specifications and Images of Selected Ultrasonic Sensors

	HC-SR04	**MB1010**	**MB1013**
Manufacturer	Various	MaxBotix	MaxBotix
Frequency	40 Hz	20 Hz	10 Hz
Sensing (Measurement) Range	0.02 m – 4 m	0.15 m - 6.45 m (6 inches - 254 inches)	0.3 m – 5 m (11.8 inches - 196.85 inches)
Distance Accuracy	Not mentioned	Not mentioned	1% or better
Resolution	3-mm (0.3 cm)	25.4 mm (1-inch)	1-mm
Operating Voltage	5V	2.5 V to 5.5 V	2.5 V to 5.5 V
Working Current	15mA	2.5mA at 2.5V to 5.5V	2.5mA at 3.3V, and 3.1mA at 5V
Internal Temperature Compensation	None	None	Yes
Image			

Upon preliminary tests of the sensors and investigating the field conditions of the construction site that was selected as the site for real-world implementation, the MB1013 ultrasonic sensor was selected as the most promising distance sensor for the formwork monitoring application. Among all the alternatives, the MB1013 sensor draws a relatively small current, which is suitable for a monitoring task that takes hours to complete. The MB1013 also provides the highest resolution (millimeter resolution) amongst the alternatives, and has an internal temperature compensation feature to calibrate the sensor readings. Lastly, the formwork components were elevated to 14 ft (4.27 m) above the lower level on the selected construction site, which is within the sensing range of the MB1013 sensor. Therefore, the remaining content below about ultrasonic sensors refers to the MB1013 sensor.

Differences between the measurements taken by the distance sensor and the data references obtained by a laser distance meter with an accuracy of 1.5mm, which are viewed as true values were observed. Hence, a linear regression analysis was performed to calibrate the ultrasonic sensor. The result is shown in Figure 4.5, the independent variable x represents the measured distance by the sensor, while the dependent variable y represents the true value as measured by the laser distance meter.

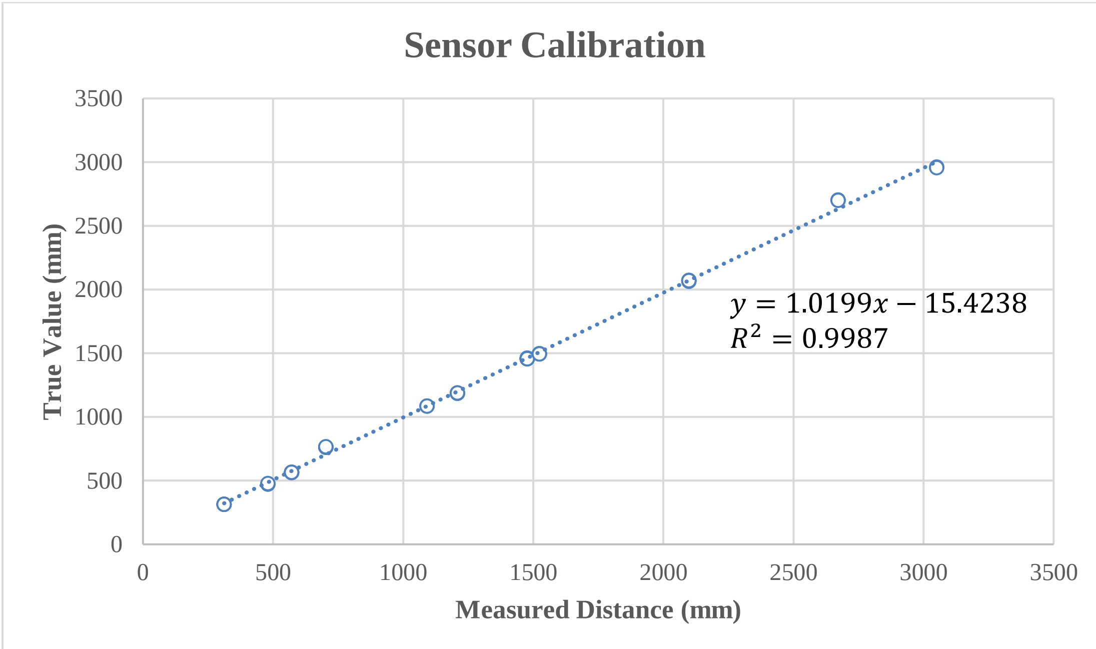


Figure 4.5. Ultrasonic Sensor Calibration Result

- **Deflection Sensor**

A resistive flex sensor is a low-cost, effective and robust option to measure bending or flexing. In a review study of resistive flex sensors conducted by Saggio et al. (2015), the main applications of flex sensors include: 1) human body tracking that are used for physical activity measurements and human-machine interactions/interfaces, 2) applications related to artificial devices, such as automotive, robotic, and musical applications, and 3) tools to measure the curvature of surfaces and flow rates, and detect damage to civil structures (e.g., buildings, bridges, tunnels, dams, etc.).

Specifically for SHM, Sasikala and Selvakumar (2014) propose using flex sensors placed on the surfaces of vertical structural components (e.g., bridge pillars), and accelerometer sensors placed on the surfaces of the ground and/or horizontal structural components (e.g., roofs, ceilings) to monitor the performance of civil structures. In their study, the sensors were mounted on a prototype pillar structure to monitor the seismic vibrations and deformation of the pillar in a lab experiment. Similarly, the work conducted by Niranjan and Rakesh (2020) proposed detecting early building collisions using flex sensors by fixing them on the center columns of a building. If the deflection in the column exceeds a pre-determined threshold, a warning will be sent through the wireless network embedded with the proposed system to the user so that the user can provide a timely response and correct the identified unsafe structural behavior. Thus, a flex sensor is promising in capturing the deflection of the vertical members (e.g., shores) in concrete formwork systems.

The displacement sensor used in the present study is a 4.4-inch long resistive flex sensor. Figure 4.6 presents how a flex sensor works. The resistance of a flex sensor changes as the sensor bends – the more it bends, the greater resistance it has (SpectraSymbol, 2014). The resistance of the flex sensor changes approximate linearly with its bending angle. In the present study, protractors were used to estimate the deflection angle, and a digital multimeter was used to obtain the corresponding resistance.

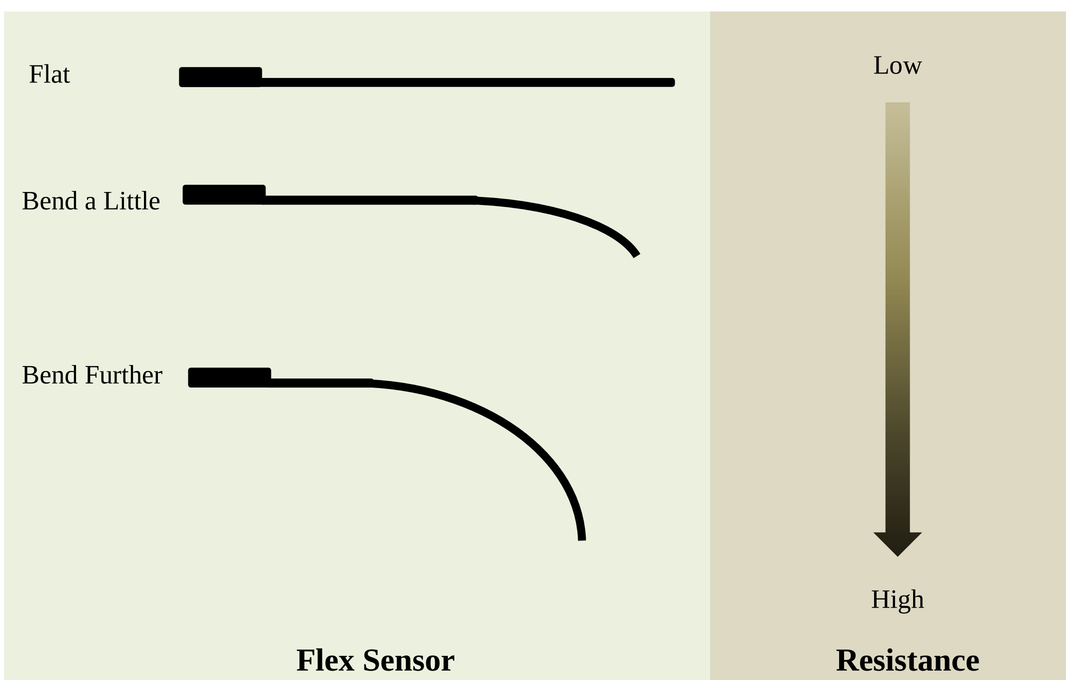


Figure 4.6. How a Flex Sensor Work (Adapted from SpectraSymbol (2014))

- **Temperature and Humidity Sensor**

For concrete construction, the mechanical properties of concrete (e.g., compressive strength) are influenced by air temperature and relative humidity during concrete placement and curing (Barroca et al., 2013), and the degree of concrete strength development has impacts on the performance of the supporting structure (Providakis and Liarakos, 2011). Thus, it is essential to monitor the temperature and relative humidity during the concrete placement and curing process.

Meanwhile, for most ultrasonic sensors, such as the HC-SR04 and MB1010 sensors (even though they were not selected for the application), no internal speed-of-sound temperature compensation is included with the sensors. However, the distance measurement obtained by an ultrasonic sensor relies on the speed of the sound, and the speed of the sound depends on temperature and humidity (Bohn, 1987). Therefore, to improve the accuracy of the measured distance with such sensors, researchers and sensor manufacturers often recommend to incorporate temperature and humidity with the measurements (Canali et al., 1982; Carullo et al., 1996; Nalini et al., 2014; Paulet et al., 2016; MaxBotix, n.d.).

In regard to this issue, the DHT22 (temperature and humidity) sensor was used, facilitating measurement of temperature and humidity during the placement of concrete. Such information could be used to adjust the calculated distances for sensors that are incapable of performing internal temperature calibrations in order to improve the data quality, and could also be used for concrete contractors to estimate the strength of the poured concrete in order to plan the removal time of the supporting concrete formwork.

However, since the temperature and humidity sensor is not integrated with the proposed sensor nodes, the temperature and humidity information collected by the sensor is viewed as less critical than the other two measurements, i.e., distance and deflection.

The content below is centered around the previous two types of sensors, i.e., distance and deflection sensors.

4.7.1.2.3 Wi-Fi Module and SD-Card Module

To allow for data transmission through a TCP/IP (Transition Control Protocol and Internet Protocol) connection through the Internet, small and low-cost 2.4GHz ESP8266 Wi-Fi modules were used in the study. As mentioned previously, data transmission rates through the Internet are determined by several factors such as network connectivity - not all the acquired data could be successfully transmitted and displayed on the desired IoT platform. Therefore, SD card shield boards were also used to allow the system to store the acquired sensors data for further analysis. The used SD card shield board includes an RTC (real time clock) that can be used to timestamp the collected data.

4.7.1.2.4 Power Supply

An independent power supply is important for applications with the WSN, as the sensor nodes need to work independently during the intended period of operation, especially when the sensor nodes are installed in a remote and/or hazardous area without connection to an existing power source (Moon et al., 2015; Kanan et al., 2018). The study adopted two units of lithium batteries (one with 3.7-V 2000 mAh, and the other one with 3.7-V 2500 mAh) to power the two proposed sensor nodes with the help of PowerBoost shields. The use of 9-V 600mAh lithium-ion batteries served as a backup power solution. Prior to field implementation, tests were performed to ensure the battery capacity is sufficient for the task of monitoring the performance of formwork during concrete placement. The test results are reported in the Section 4.7.2.1.3.

4.7.1.2.5 Assembly

After all the sensors were selected and tested, they were assembled based on the proposed design (Figure 4.3). Figure 4.7 illustrates the circuit and schematic diagrams for the proposed sensor node 1 that is used to measure the distance between the bottom of the formwork and the ground/lower level, and Figure 4.8 presents the assembled sensor node using an MB1013 ultrasonic sensor, a Wi-Fi module (ESP 8266), a stackable SD card shield, and a PowerBoost shield with a lithium battery. Since the sensor node needs to be installed at the bottom of a sheathing panel to measure the distance, a 4” × 4” × 2” junction box was used. The main part of the sensor node including the Arduino board and its stackable shields are placed inside the box. The breadboard with the ultrasonic sensor used is placed outside the box, facing down towards the ground, as shown in Figure 4.9. This setting was used in both lab experiments and field implementation.

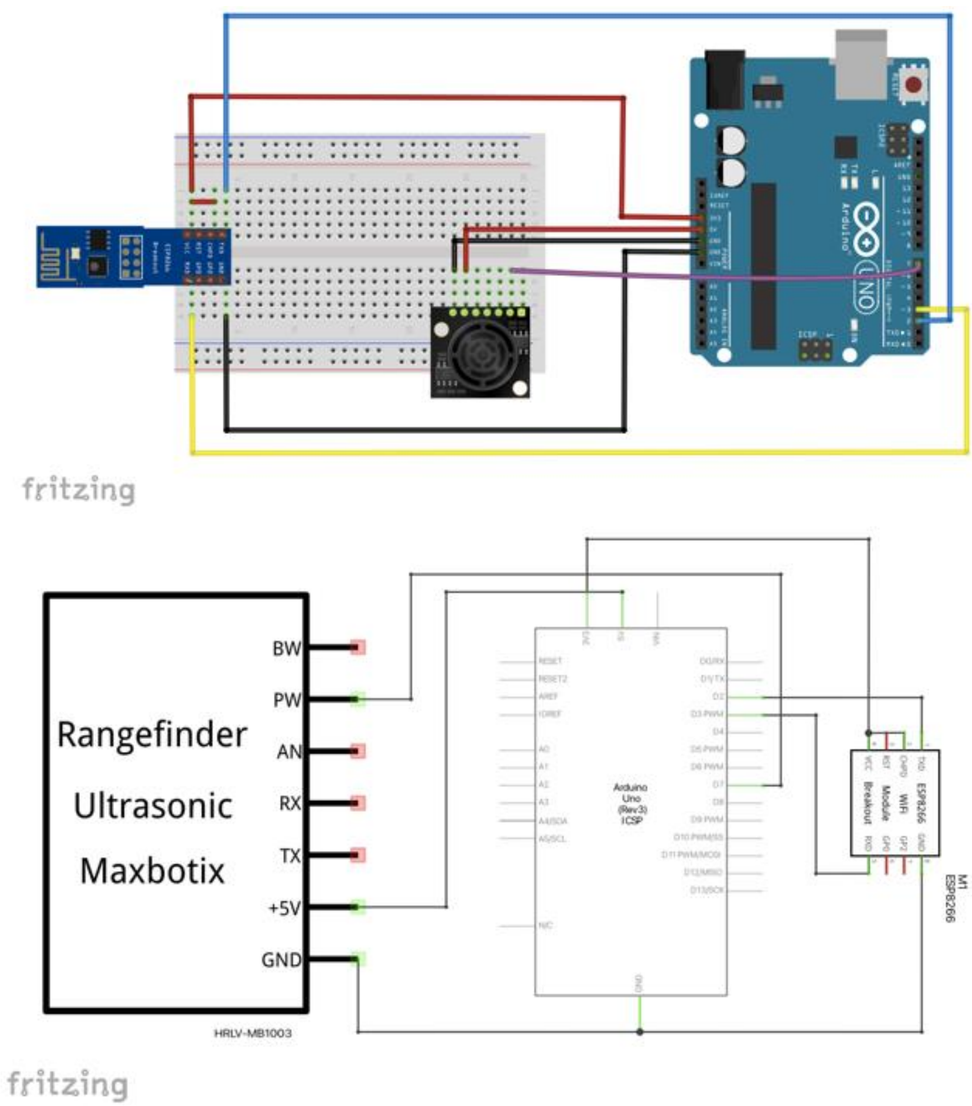


Figure 4.7. Ultrasonic Sensor Circuit and Schematic Diagrams

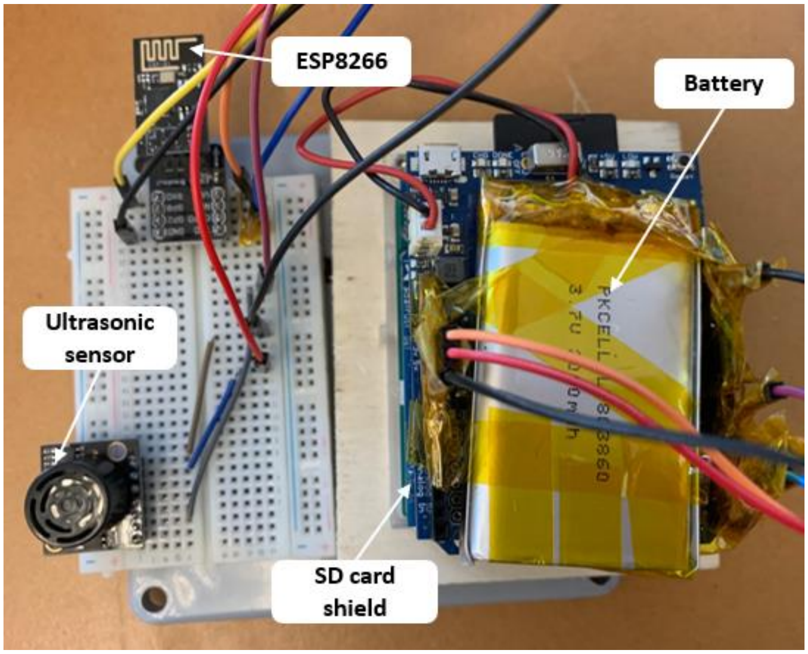


Figure 4.8. Assembled Sensor Node for Measuring Distance

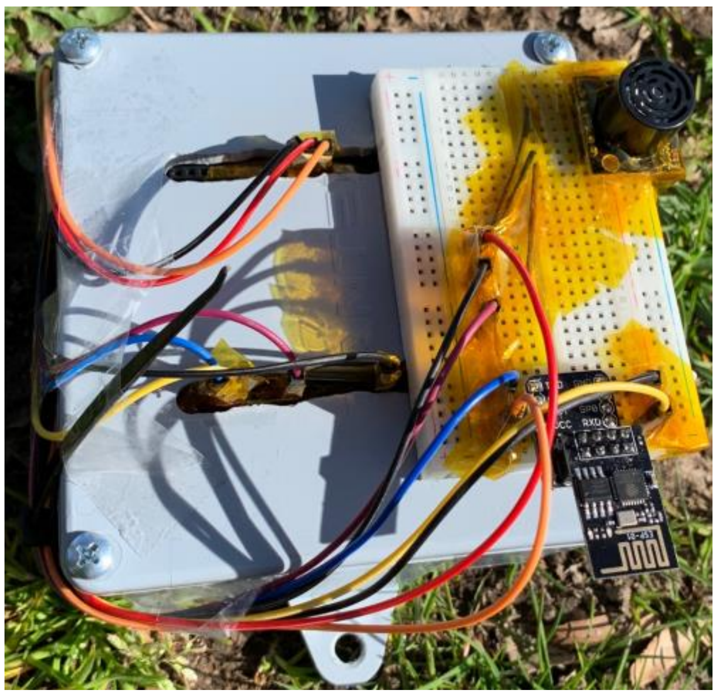


Figure 4.9. Assembled Sensor Node for Measuring Distance with a Junction Box

As for sensor node 2, which is used to measure the deflection of a shoring post, Figure 4.10 displays the circuit and schematic diagrams, and Figure 4.11 presents the assembled sensor node using a flex sensor. The assembled node includes a flex sensor, a Wi-Fi module (ESP 8266), a stackable SD card shield, and a PowerBoost shield with a lithium battery, similar to the sensor node with the ultrasonic sensor. It is worth mentioning the flex sensor shown in the Figure 4.11 is a 3-inch long flex sensor. In the lab and field experiments, a longer flex sensor (4.4-inch) was used.

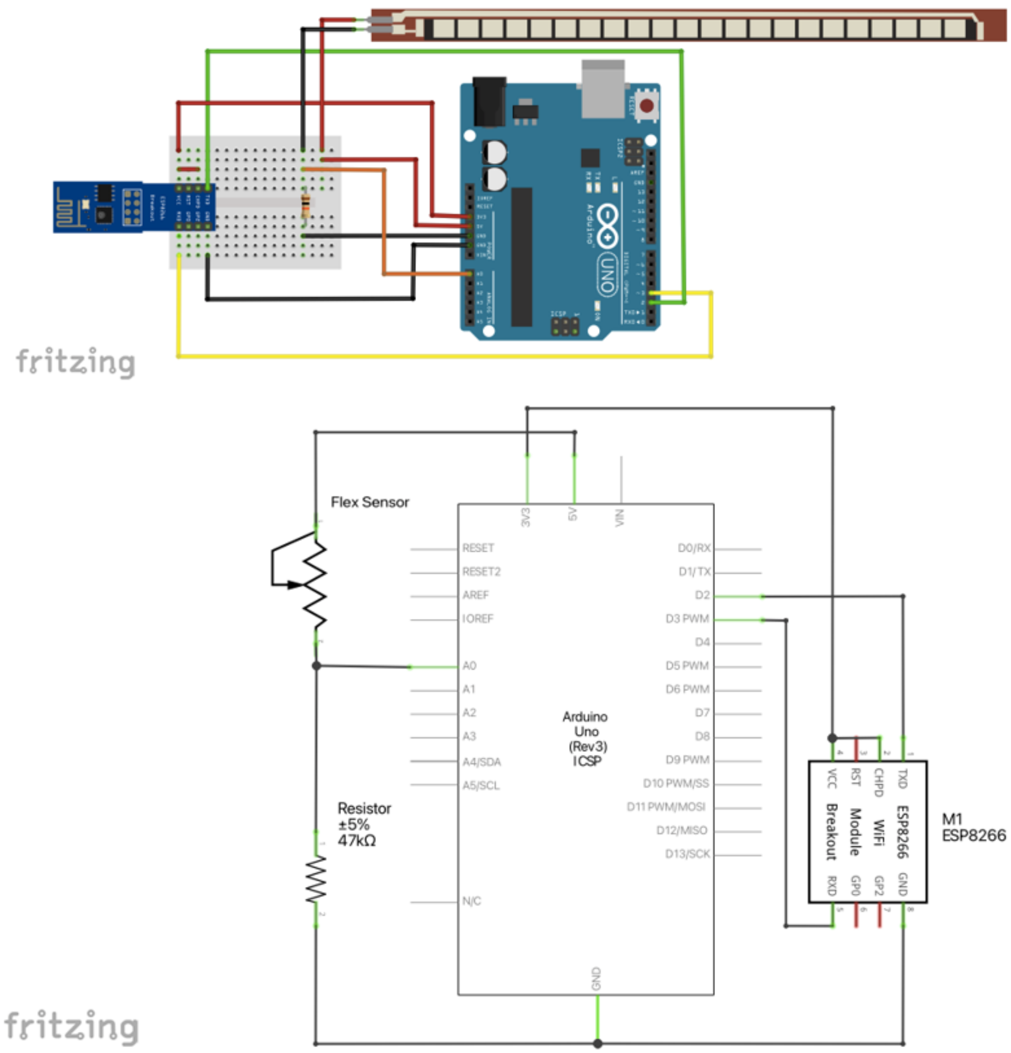


Figure 4.10. Flex Sensor Circuit and Schematic Diagrams

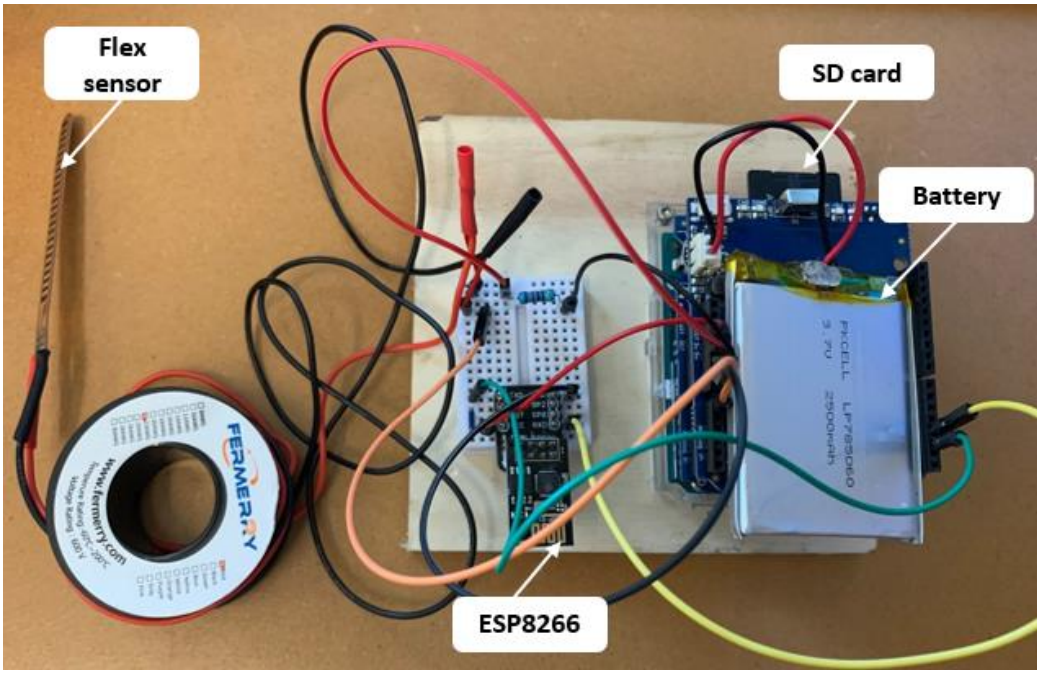


Figure 4.11. Assembled Sensor Node for Measuring Deflection

4.7.1.3 IoT Channel Creation

On the Thingspeak platform, a channel is where the user can send the data to store and display. Therefore, for the proposed real-time monitoring system, a new channel was created to collect and visualize the data obtained by the sensors. The following four fields are included in the channel, as shown in Figure 4.12.

- Field 1: Temperature (°C)
- Field 2: Humidity (%)
- Field 3: Distance (mm)
- Field 4: Estimated Deflection Angle (degree)

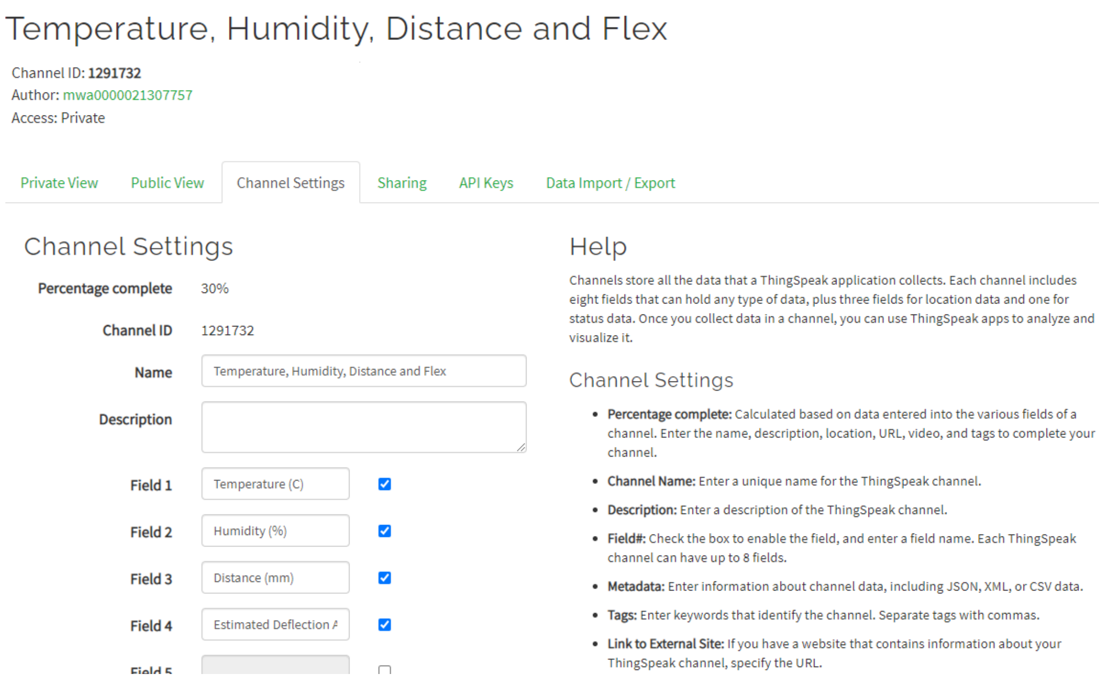


Figure 4.12. Screenshot of the Created Thingspeak Channel

4.7.1.4 Software System

Programming codes were written with the Arduino IDE (Integrated Development Environment) in languages C/C++. The coding was uploaded to the Arduino boards to take measurements, store the measurements in the SD cards, and transmit the data to the created Thingspeak channel. For the two proposed sensor nodes, in general, the scripts contain three major components: 1) scripts to read data from sensor(s), 2) scripts to setup an SD card and to store the acquired readings, along with the dates/times when the readings are taken, and 3) scripts to configure the Internet connection and send the acquired readings to the created Thingspeak channel. Example scripts to read a flex sensor, store the readings and transmit the data to a Thingspeak channel can be found in Appendix III.

When generating and testing the codes, it was noticed that the codes used to accomplish the abovementioned tasks (e.g., reading sensor data, configuring an SD card and the Internet, saving sensor data to the SD card, etc.) takes considerable program storage space in the Arduino UNO microcontroller (71% for the ultrasonic sensor, and 74% for the flex sensor), as well as the dynamic memory (72% for the ultrasonic sensor, and

74% for the flex sensor). This issue may cause stability problems, which was discussed extensively online, such as in the Arduino Forum (2015). The large amount of storage space required also limits the capability of incorporating more features in the sensor nodes, such as data processing and analysis in real-time. Therefore, as an exploratory study, the focus was placed on the capability of data acquisition with the proposed WSN monitoring system. The sensor data were saved and then downloaded later for further analysis.

4.7.2 Experiments

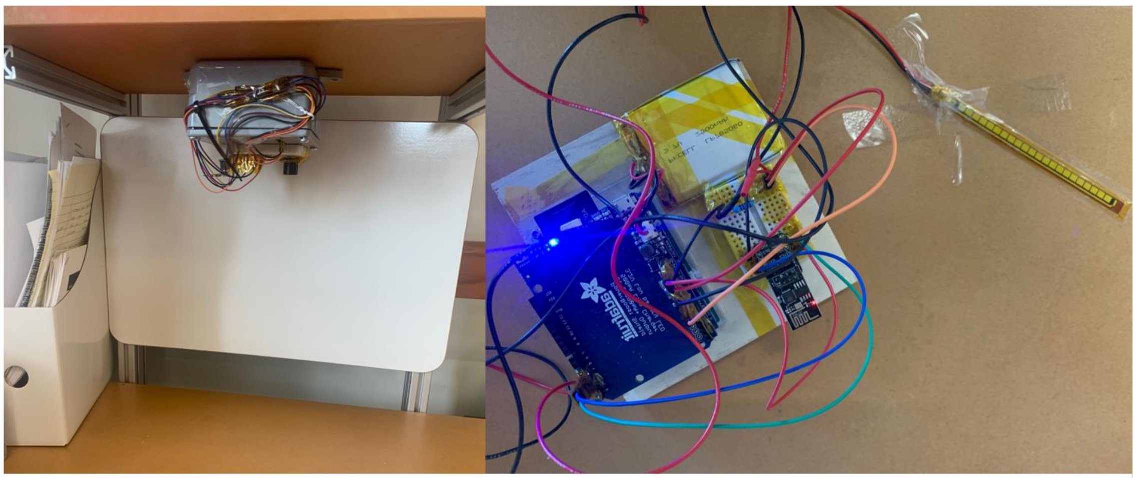
Both the lab experiments and field implementation were conducted to confirm the workability of the proposed sensor nodes, and to verify the usefulness of the proposed real-time formwork monitoring system. It is worth mentioning that the work presented is at its preliminary stage – the acquired sensor data are analyzed and interpreted after the experiment is completed. Future work needs to be conducted to provide real-time recommended responses to the user based on the real-time analysis with the obtained sensor data.

4.7.2.1 Lab Experiment

Before conducting field data collection with the proposed system on a real construction project, several lab experiments were conducted to test the performance of the sensors, to find an appropriate filter to ensure data quality, and to ensure the battery life is adequate for the course of data collection during concrete placement.

4.7.2.1.1 Lab Experimental Setting

Figure 4.13 shows two lab experiment examples. As shown in the Figure 4.13(a) (left), the junction box with all the sensor units was placed under a shelf to estimate the distance between the shelf and the desk surface below. In the Figure 4.13(b) (right), a flat flex sensor was attached to the surface of the desk with tape to maintain its shape during the experiment. Similar experiment settings were used to obtain more data when sensors were placed in a steady state condition. For each experiment setting, in addition to the measurements obtained by the sensors, a data reference to compare against the sensor measurements was obtained with a commercially available tool. For instance, a Leica DISTO D2 laser distance meter was used to measure the distance, an ATPro air quality monitor was used to provide the temperature and humidity values, and protractors were used to estimate the deflection angle, as shown in Figure 4.14. Fifty samples were taken for each experiment setting, and the sample measurement results are presented in Figure 4.15 and Figure 4.16.



(a). Ultrasonic Sensor Placed Under a Shelf in Testing (b). Flex Sensor (Flat) in Testing

Figure 4.13. Lab Experiment Examples

Figure 4.14. Tools and Instruments Used to Obtain Data References

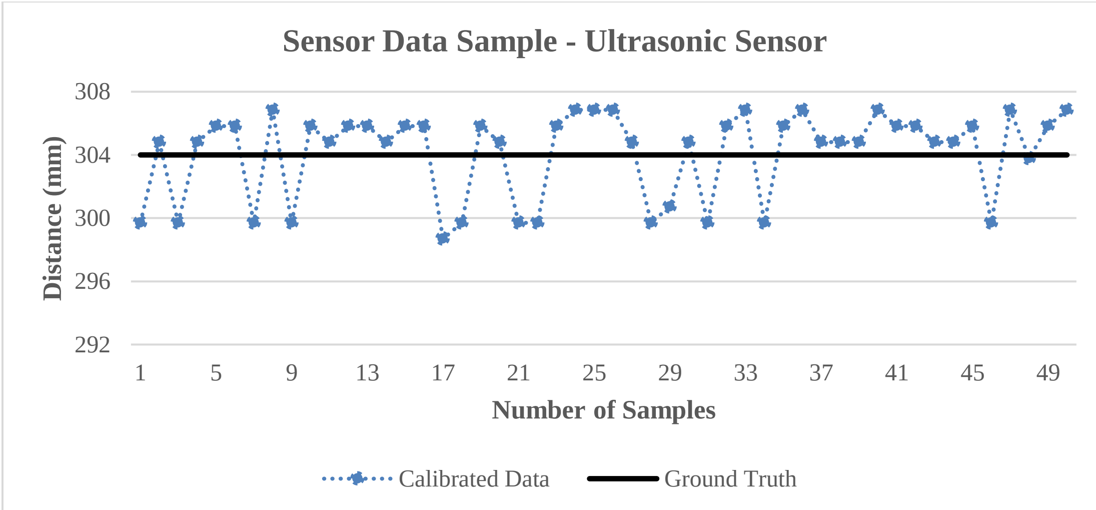


Figure 4.15. Calibrated Sensor Data Sample (Ultrasonic Sensor)

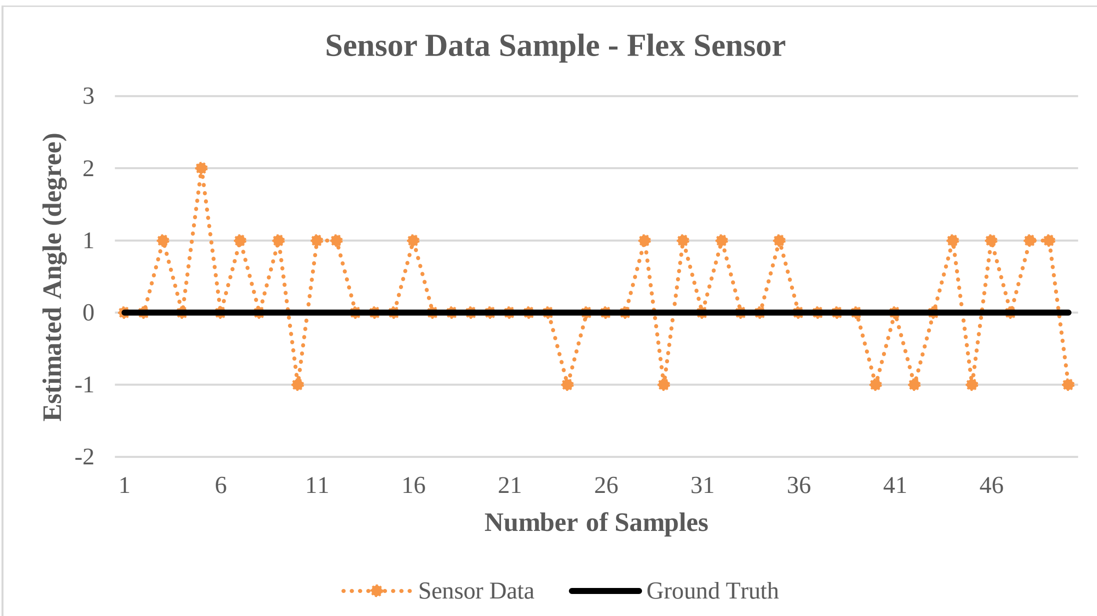


Figure 4.16. Sensor Data Sample (Flex Sensor)

4.7.2.1.2 Sensor Signal Processing and Filtering Method

Sensors are often sensitive to external noises and other confounding factors, which may result in a series of noisy measurements, as can be observed in Figure 4.15. For instance, the readings provided by ultrasonic sensors which are based on time-to-flight of an ultrasonic sound wave, were influenced by air composition, external shocks, amplitude attenuation and shape distortion of ultrasonic echo, temperature and humidity (Angrisani et al., 2006; Kim and Choi, 2008; Khoenkaw and Pramokchon, 2017). One solution to improve the stability, reliability and accuracy of sensor measurements is to use digital signal processing method. The commonly-used digital signal process methods include low-pass filter (LPF), moving average filter, moving median filter, and Kalman filter.

The Kalman filter, a recursive predictive filter developed by Rudolf E. Kalman (Kalman, 1960), is widely used in industry applications for guidance and navigation systems, computer vision systems, and signal processing and instrumentation (Auger et al., 2013). Studies on the application of the Kalman filter to sensors (e.g., ultrasonic sensors, flex sensors, and temperature/humidity sensors) have been carried out previously. Examples include Avinash et al.’s (2015) study on WSN temperature monitoring solution, Iswanto et al.'s (2019) study on real-time water level monitoring using ultrasonic sensors, and Zhao and Wang's (2012) study on motion measurements with an integrated system that consists of accelerometers, gyroscopes, magnetometers, and ultrasonic sensors using a nonlinear version of the Kalman filter titled the extended Kalman filter (EKF). Therefore, using the Kalman filter for the present study on the selected sensors of the proposed monitoring system is promising.

According to Welch and Bishop (1995), the discrete Kalman filter is designed to estimate the state of a discrete-time controlled process by using a measurement, with consideration given to process and measurement noises. The two noises are assumed to follow normal distributions, and they are independent of each other.

The Kalman filter process is recursive as it uses a form of feedback control with two main distinct processes, namely, the prediction process and the update process. Figure 4.17 presents a simplified graphic explanation of the discrete Kalman filter. The filter provides the state estimate for time k ahead in time (at time k-1), and obtains feedback by incorporating a new measurement (at time k) to get an improved estimate for the state at time k.

To use the Kalman filter, the system model is assumed to obey the following linear stochastic equation:

$$x_{k+1} = Ax_k + Bu_k + w_k \tag{3}$$

where x_k is the estimate at step k, A is the state transition model matrix, u_k represents control inputs, B is the optional control matrix, and w_k is the process noise. Also w_k is assumed to be a zero-mean normal distribution with the covariance Q. That being said, $w_k \sim$ N (0, Q).

Then, the measurements obtained by the sensors are assumed to follow a linear function as follows:

$$z_k = Hx_k + v_k \tag{4}$$

where z_k is the measurement value at step k, H represents the measurement model matrix, and v_k represents the measurement noise. The measurement noise v_k is assumed to follow the normal distribution with zero-mean and covariance R, i.e., $v_k \sim$ N (0, R).

Once the models are setup, the initial assumptions including the initial state estimate ($\hat{x}_{0,0}$) and the initial model uncertainty ($P_{0,0}$), also known as initial error covariance, are made. In the prediction stage, two equations are used to project the state (Equation (*5*)) and the estimate uncertainty (Equation (*6*)) for the next time step.

$$\hat{x}_{k+1,k} = A\hat{x}_{k,k} + Bu_k \tag{5}$$

where $\hat{x}_{k+1,k}$ is the predicted state estimate for the next time step k + 1 at time k, and $\hat{x}_{k,k}$ is an estimate of x in the current state (time step k).

$$P_{k+1,k} = AP_{k,k}A^T + Q \tag{6}$$

where $P_{k+1,k}$ is the predicted error covariance for the next time step k + 1 at time k, $P_{k,k}$ is the estimate error covariance of the current state (time step k), and Q is the process noise.

Then, in the update phase, the Kalman gain at time step k + 1, K_{k+1}, can be computed based on Equation (*7*).

$$K_{k+1} = P_{k+1,k}H^T(HP_{k+1,k}H^T + R)^{-1} \quad (7)$$

where $P_{k+1,k}$ is the error covariance estimated at time step k of the current state (time step k + 1), H is an observation matrix, and R is a measurement uncertainty.

With a measurement Z_{k+1}, which represents the measurement taken at time k, the updated estimate state at the current state (time step k + 1), $\hat{x}_{k+1,k+1}$, could be obtained by:

$$\hat{x}_{k+1,k+1} = \hat{x}_{k+1,k} + K_{k+1}(Z_{k+1} - H\hat{x}_{k+1,k}) \quad (8)$$

where $\hat{x}_{k+1,k}$ is the predicted state estimate for the current state (time step k + 1) at the previous state (time step k), which is calculated from Equation (5), and K_{k+1} is a Kalman gain for time step k + 1, which is calculated from Equation (8).

The updated error covariance at the current state (time step k +1), $P_{k+1,k+1}$ can then be calculated based on Equation (9).

$$P_{k+1,k+1} = (1 - K_{k+1}H)P_{k+1,k} \quad (9)$$

where $P_{k+1,k}$ is the predicted error covariance from the previous time step (time step k), which is obtained from Equation (6). Then the system goes to the prediction stage, and the process is repeated at every time step.

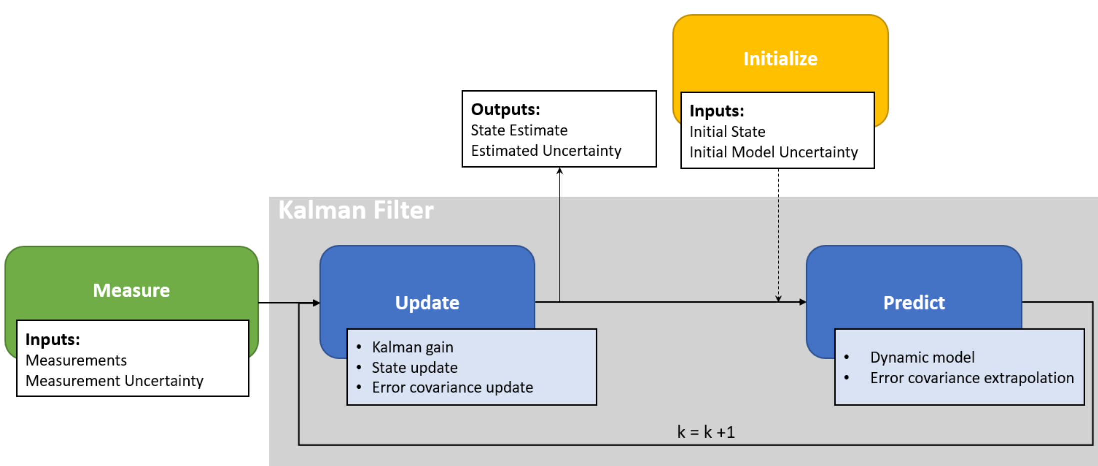


Figure 4.17. Graph Explanation of the Kalman Filter (Modified from Alex Becker (2018))

For the purpose of the present study, a one-dimensional Kalman filter was implemented, similar to what was performed in the studies by Galanis and Anadranistakis (2002), Khan et al. (2018) and Al Tahtawi (2018). The initial model assumes an order of one with the following parameters, A = 1, B = 0, and H = 1. Substituting the parameters into Equations (*4*) – (*9*), the equations are as follows:

$$x_{k+1} = x_k + w_k \quad (10)$$

$$z_k = x_k + v_k \quad (11)$$

$$\hat{x}_{k+1,k} = \hat{x}_{k,k} \quad (12)$$

$$P_{k+1,k} = P_{k,k} + Q \quad (13)$$

$$K_{k+1} = P_{k+1,k}(P_{k+1,k} + R)^{-1} \quad (14)$$

$$\hat{x}_{k+1,k+1} = \hat{x}_{k+1,k} + K_{k+1}\left(Z_{k+1} - \hat{x}_{k+1,k}\right) \quad (15)$$

$$P_{k+1,k+1} = (1 - K_{k+1})P_{k+1,k} \quad (16)$$

4.7.2.1.3 Result

Through a series of trials with the parameters, for the ultrasonic sensor and for a nearly steady-state condition, the process noise covariance (Q) is set to 1e-06 to consider potential small fluctuations that may occur between two consecutive time steps. For an unsteady-state condition, to account for the uncertainty of the system model (Equation (*10*)) due to state changes between two consecutive time steps, the process noise is increased to 1e-03. As for measurement uncertainty (R), it is equal to the sample variance from the data obtained by the sensor. Figure 4.18 presents the filtering result using the described one-dimensional Kalman filter on the same dataset plotted in Figure 4.15. It can be observed that the use of the Kalman filter is able to remove noises from the calibrated sensor data, and the estimated values converge towards the true value after a few iterations.

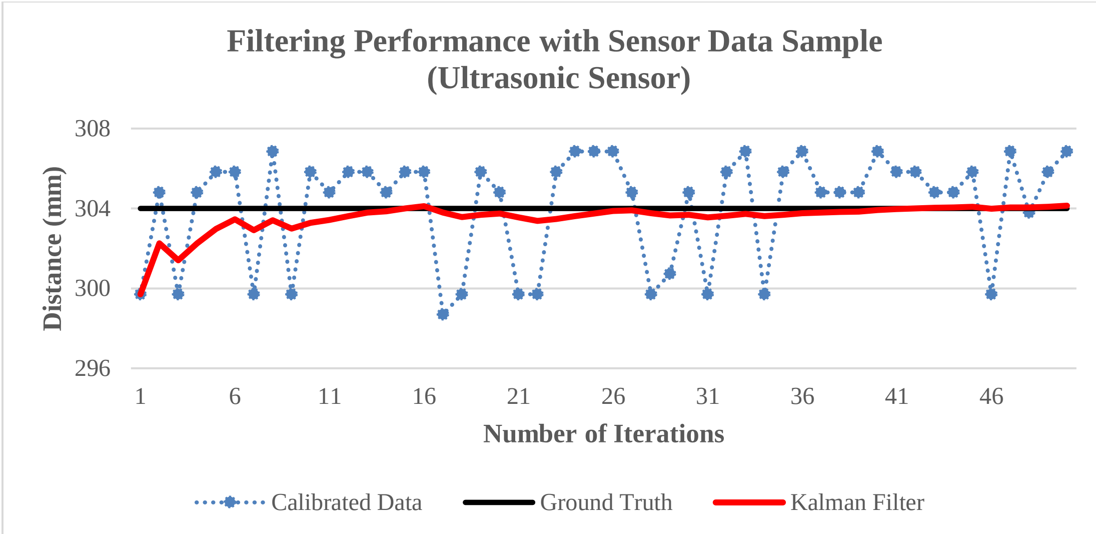


Figure 4.18. Filtering Performance with a Sensor Data Sample (Ultrasonic Sensor)

Similarly, for the flex sensor, as shown in Figure 4.19, the Kalman filter performs well in reducing data uncertainty contained in the sensor data. The estimations converge towards the true value after a few iterations. It is worth mentioning that the estimations obtained from the Kalman filter may not match the exact condition. However, compared to the original noisy measurements, the estimations generated by the Kalman filter provide a much closer approximation to the truth. Therefore, the estimations generated by the Kalman filter can be used for making informed decisions.

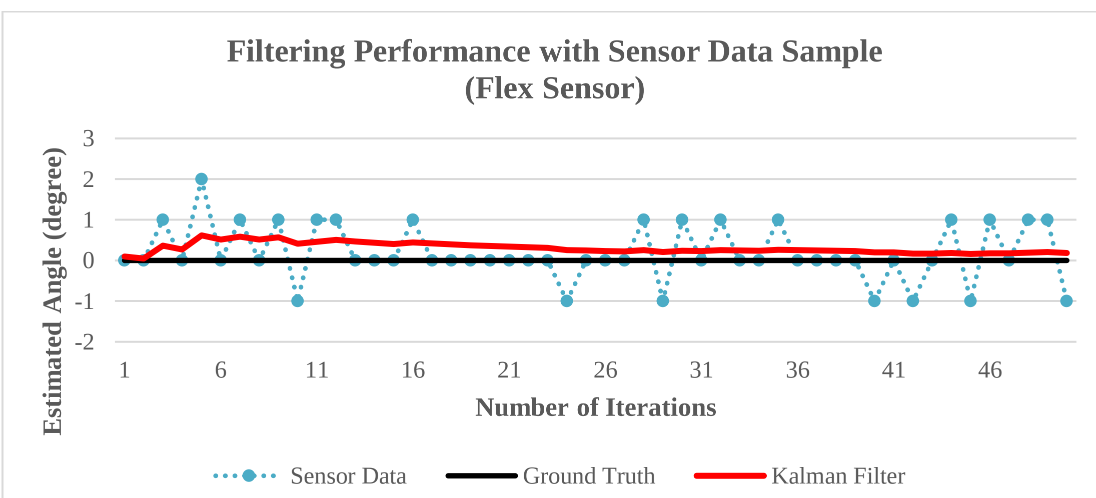


Figure 4.19. Filtering Performance with a Sensor Data Sample (Flex Sensor)

Moreover, battery tests show that the 3.7-V 2000 mAh battery lasted 13 to 14 hours for the ultrasonic sensor (sensor node 1), and the 3.7-V 2500 mAh battery lasted 10 to 11 hours for the flex sensor (sensor node 2). Therefore, the power supplies to the two main sensor nodes should be more than sufficient for one-day formwork monitoring during concrete placement (8-hour operation). The 9-V 600 mAh lithium-ion was used to power the temperature/humidity sensor only, and the duration was 5.5 to 6 hours. Backup batteries are needed for the temperature/humidity sensor.

4.7.2.2 Field Implementation

The proposed system was then implemented and tested on a construction site in Tacoma, WA to demonstrate its workability and to verify the usability of the proposed real-time formwork monitoring system. The construction project is a six-story mixed-use building that consists of 156 apartment units and a 3,500-sf ground level retail space. The project is designed to have concrete construction for the first story with wood-frame construction from the second story to the top. The proposed real-time monitoring system was tested during the pouring for the second-floor level (first elevated floor) concrete slab. Based on the type of formwork used and the formwork manufacturer’s calculations, the maximum deflection should not exceed the span of the form component divided by 270. As for the deflection of a shoring post, 5° is set as the maximum allowable limit, as Moon et al. (2015) suggested that the 5° inclination of a shoring support is an indicator of an unsafe condition.

4.7.2.2.1 Sensor Installation and Implementation

Concrete placement on the project started at approximately 07:10 AM, and finished at around 03:30 PM. The sensor was installed before the start of concrete placement and removed after the work was complete. The monitoring lasted for about 8 hours. The sensor data were collected every 10 seconds and stored in the SD cards that were embedded with the system, and transmitted to the established Thingspeak channel.

Figure 4.20 shows the setup of the system during the experiment. The junction box which contains all the elements for sensor node 1 (Figure 4.20(a)) was attached to the bottom of a sheathing panel using screws and double-sided adhesive tape, with the ultrasonic sensor facing down, toward the ground, to measure the distance between the sensor and the ground. The flex sensor was installed on an adjacent shoring post with tape to measure the deflection of the shoring post as an indicator of the stability of the slab formwork system. A separate temperature/humidity sensor, carried by the author, was used to record the environmental data around the construction site and transmit the data to the Thingspeak channel. The temperature/humidity sensor was not physically installed on the monitored formwork system during the field implementation. Figure 4.21 shows the concrete placement in progress on the site.

Figure 4.20. Field Experimental Setup

Figure 4.21. Concrete Placement in Progress

During the field implementation, the cellular data connection of the researcher's personal cellphone was used as a hotspot, so that all the sensor nodes could be connected to the Internet and the data published to the Thingspeak channel. It is essential for the user to check periodically whether all the sensor nodes were successfully connected to the Internet. Figure 4.22 presents a screenshot that all three sensor nodes (the distance sensor, the flex sensor, and the temperature/humidity sensor) were connected successfully to the hotspot during the experiment. Through the wireless connection, the transmitted data regarding the real-time temperature, humidity, measured distance, and estimated deflection angle, could be accessed through the web or mobile. Figure 4.23 presents a screenshot of the real-time data (temperature and humidity) on the Thingspeak channel.

Figure 4.22. Sensor Node Connections to the Hotspot

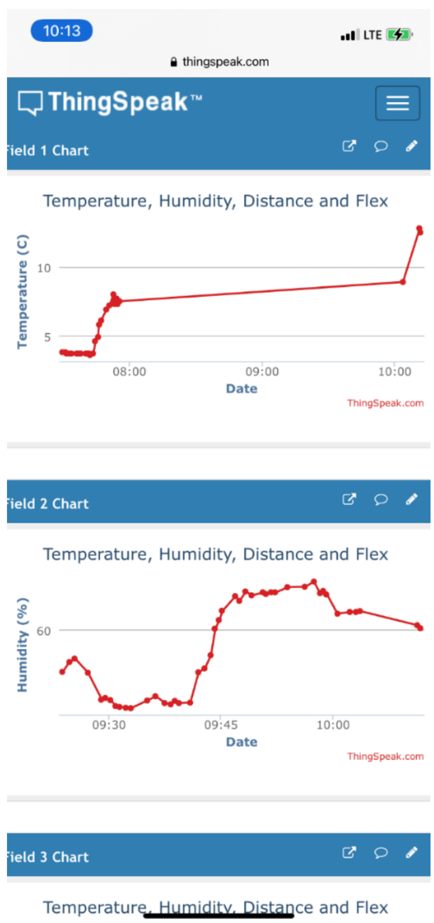


Figure 4.23. Screenshot of Real-Time Data on the Thingspeak Channel

4.7.2.2.2 Data Analysis and Result

Figure 4.24 and Figure 4.25 present the field implementation results regarding the displacement of the horizontal slab formwork component, i.e., a sheathing panel, and the deflection of the vertical formwork component, i.e., a shoring post, respectively. The sensor nodes were placed approximately 20 minutes before the start of concrete placement (pour started around 07:10 AM). The first 10-minutes of data were used for the Kalman filter to converge towards the true values. As a result, the distance and deflection information of the monitored components obtained at around 07:00 AM were used as the start status of the monitored formwork components before they were exposed to the pressure of the construction operations.

As can be observed in Figure 4.24, the monitored sheathing panel deflected during the concrete placement, which was reflected by the measured displacement. However, the deformations fell within the allowable maximum limits prescribed by the formwork manufacturer. The fastest and the largest change in terms of displacement occurred when the concrete placement occurred directly above the sensor node location. The average estimated absolute displacement was 0.71 mm, with a maximum displacement of 1.50 mm. In Figure 4.24, the upper limit (black dashed line) represents the allowable maximum displacement when the monitored panel bends downward (sags), and the lower limit (grey dashed line) represents the allowable maximum displacement when the monitored panel bends upward (hogs).

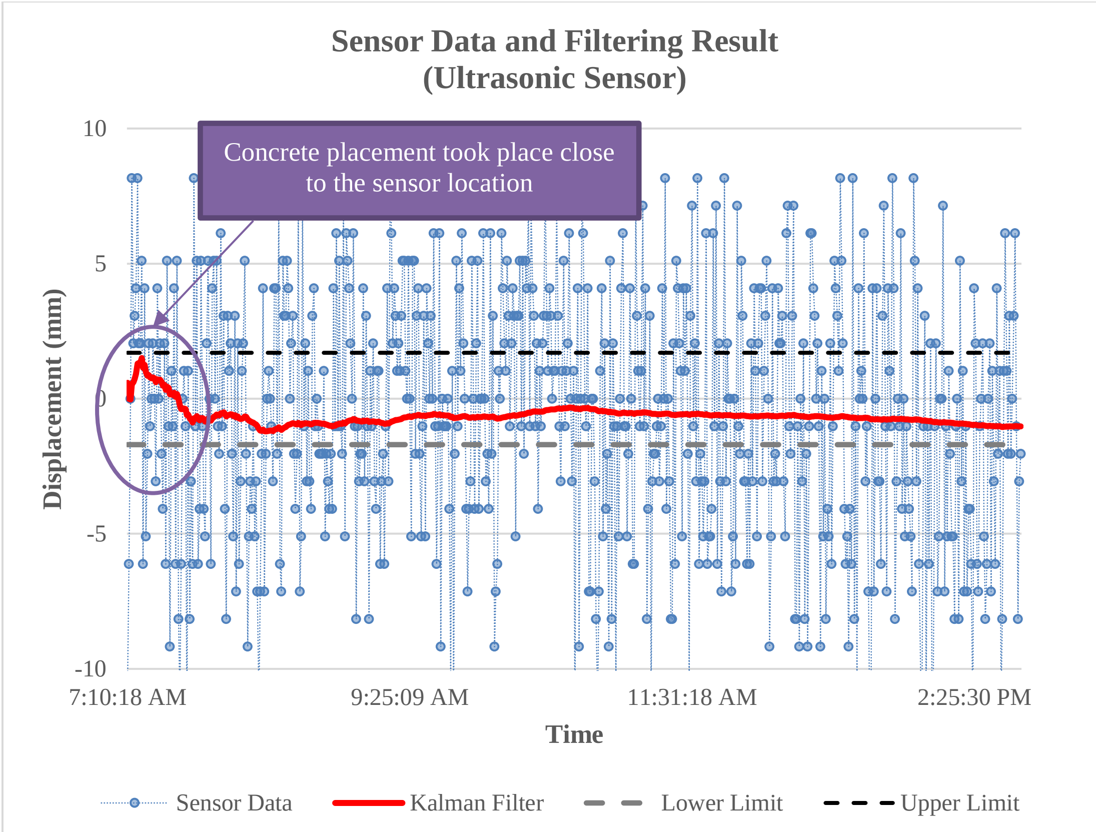


Figure 4.24. Field Data and Filtering Result (Displacement of a Horizontal Slab Formwork Component)

A similar trend can be observed for the monitored shoring post. As shown in Figure 4.25, the largest change to the post in terms of deflection angle occurred at the same time period – when the concrete placement activities occurred close to the sensor node location. A slight change to the shoring post could be observed from the figure, with an average estimated absolute change of 0.72 degrees, and a maximum change of 1.48 degrees. The result reveals that the deflection of the shoring post was controlled within the maximum allowable limit of 5 degrees.

The analysis of the measurement values show that the concrete placement were within the control limits – the deformations of the investigated concrete formwork components were both within the allowable limits. No structural instability issues were observed and recorded during the field implementation and concrete curing phases, which is consistent with the findings presented in the study.

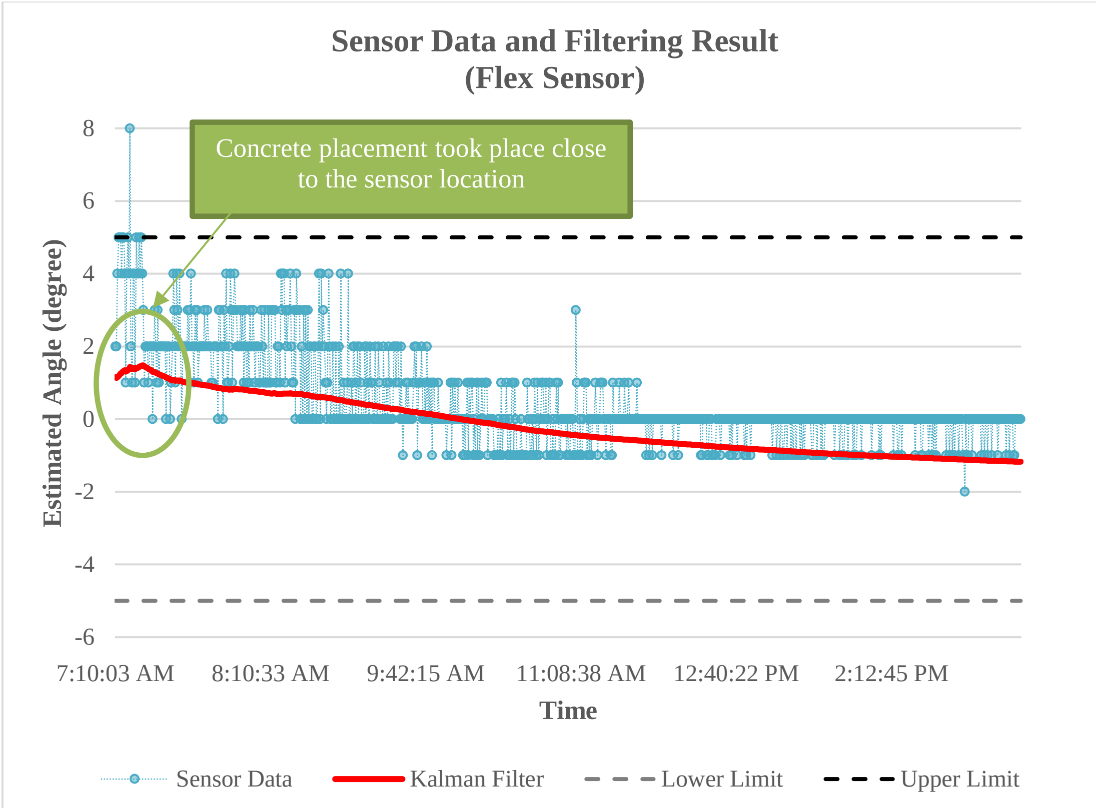


Figure 4.25. Field Data and Filtering Result (Deflection of a Shoring Post)

4.8 Discussion

4.8.1 Technology Selection

Researchers have made several attempts to apply advanced technologies to improve the inspection and monitoring performance of temporary structures, similar to what has been performed to confirm the structural health of permanent structures. However, none of the previous studies placed a focus on making an appropriate technology selection decision among various technology alternatives for the monitoring task associated with temporary structures. This study proposes a decision-making approach using fuzzy set theory to address the uncertainties and vagueness within the MCDM process. A hypothetical case scenario was adopted to demonstrate the technology selection process for concrete formwork monitoring. Some limitations were identified throughout the decision-making process, and are presented as follows.

One limitation present in the technology selection lies in the determination of potential technologies that could be applied to concrete formwork monitoring. It is hypothesized that construction innovations that show promising results when applying the technologies to SHM for permanent structures could also be used to monitor the performance of temporary structures. However, to date, only limited technologies have been examined for temporary structures monitoring.

With respect to the relative ratings of the importance of technology selection criteria, and the alternative preference, the process of achieving the relative ratings is not straightforward; the former was obtained through the conversion of responses from a Likert question in an expert survey using RII values, and the latter was determined based on a literature review. Using a literature review to determine the performance ratings of technology alternatives was similar to that done by Kopsida et al. (2015). It satisfied the needs of the present exploratory study as it attempts to show how to solve a technology selection problem for concrete formwork monitoring. However, when applying a similar method in real-world cases, other methods such as surveys of experts or decision-makers may be more appropriate to obtain accurate ratings. Moreover, when applying the fuzzy set theory in the decision-making process, the results mainly rely on the judgement of humans. As a result, bias exists within the assessment data. The assessment data are subjective and not acquired from empirical evidence, which makes it hard to validate the selection results (Eierdanz et al. 2008). Additionally, other individual, organization and technology factors apart from the identified technology selection criteria, such as the size of the project, complexity of the temporary structure, technology brand and durability, and top management involvement and support, may also influence the adoption and selection of technologies (Nnaji et al., 2018a). The selection process should be considered on a case-by-case basis.

4.8.2 Real-Time Monitoring System

Building upon the technology selection result, a real-time WSN monitoring system was developed to monitor the performance of concrete formwork during the placement of concrete. By implementing the proposed system on a construction site during slab pouring, it is shown that the proposed system offers an improved approach to monitor the structural stability of formwork components through real-time data acquisition and visualization. The benefits and limitations of the proposed monitoring system discovered throughout the development and implementation phases are presented below.

4.8.2.1 Ease of Use

The proposed WSN monitoring system is easy to acquire, build, and use. The hardware and software used are all commercially available and open-source. Once the sensor nodes are correctly configured and powered on, the installation process takes less than 10 minutes to complete. During the monitoring phase, the proposed system provides real-time data on the structural behavior of the monitored formwork components. The data were transmitted to a designated IoT channel that enables easy access for multiple parties (e.g., contractors, formwork designers, etc.). Interested parties can access the data remotely without being physically present on the construction site during the operation. The designed system facilitates continuous monitoring process and enhances the potential for real-time collaboration between the project team members regarding formwork performance.

However, as described previously, the structural instability conditions could not be determined in real-time in the current form of the developed monitoring tool. Future studies are expected to incorporate the signal processing and filtering method for real-time data interpretation. Early warnings of structural failures could be triggered based on the collected and analyzed data.

In addition, when monitoring the structural behaviors of multiple horizontal and/or vertical formwork components, publishing monitoring data on the Thingspeak channel may not be a good option. It is true that data obtained by different sensor nodes could be published in different data fields, as shown in Figure 4.12. However, it could be very difficult to locate the corresponding formwork component when looking at a specific data field on the Thingspeak channel, especially for the conditions that immediate corrections or responses are required for a detected potential structural failure. In regard to this issue, the integration of the proposed WSN system and BIM or other visualization platform is expected. This integration could help visualize the performance of the monitored components, accomplish real-time information sharing and communication, and improve the monitoring experiences.

4.8.2.2 Cost

Table 4.7 lists the itemized cost of components used in the field implementation. The major system components include three Arduino UNO boards, three Wi-Fi modules and their breadboard adapters, one ultrasonic sensor, one flex sensor, one temperature/humidity sensor, two stackable SD card shields, two PowerBoost shields, and batteries to power the sensor nodes during the field implementation. The total cost is around $243 (tax not included).

Table 4.7. Cost of the Proposed Real-Time Formwork Monitoring System

Item	**Unit Cost**	**Units**	**Total Cost**
Arduino UNO	$23.00	3	$69.00
Wi-Fi module (ESP8266) and its breadboard adapter	~$2.10	3	~$6.30
Ultrasonic sensor	$37.95	1	$37.95
Flex sensor	$15.95	1	$15.95
Temperature/Humidity sensor	~$6.00	1	~$6.00
SD Card shield	$13.95	2	$27.90
PowerBoost shield	$19.95	2	$39.90
Batteries	$12.50	1	$12.50
	$14.95	1	$14.95
	~$6.00	2	~$12.00
		Total	$242.45

Costs of labor for the sensor assembly and installation, as well as accessories (e.g., breadboards, jump wires, hook-up wires, heat shrinks, an Arduino and breadboard holder, a junction box, tapers, and screws) are omitted. The cost of network services, i.e., cost of cellular data plan, is also excluded. Since no commercially available formwork monitoring tool is capable of acquiring similar formwork information during the operation, a cost comparison could not be made directly. Nevertheless, when considering the human effort involved in the traditional formwork monitoring practices, the low-quality monitoring results, and the possible loss in terms of time, cost, and human life if structural failure occurs, the cost of the proposed real-time formwork monitoring system is worthwhile for such an application.

4.8.2.3 Data Loss

After downloading the data from the Thingspeak channel, it was found that not all sensory data were successfully transmitted to the channel - some transmission or reception disruption occurred during the field implementation. The researcher's cellphone served as a mobile hotspot to provide internet connections for the sensor nodes during the field implementation. Even though the hotspot was present near the construction site throughout the duration of the field implementation, data interruptions occurred for all three sensor nodes (Table 4.8). Another possible reason for data loss during transmission is that, currently, the data update interval for the Thingspeak channel is limited to one update every 15 seconds for a free license (ThingSpeak, 2021). For an application that sends data from multiple sensor nodes, data loss may occur because of the transmission limit.

Table 4.8. Summary of Data Transmission during the Field Implementation

Sensor	**Transmission Time (Seconds)**			**Notes**
	Minimum	**Mean**	**Maximum**	
Temperature and Humidity Sensor	16	68	1688	The sensor was fairly close to the hotspot (less than 3 feet)
Ultrasonic Sensor	15	382	2728	The sensor was placed installed under the bottom of a sheathing panel (~ 4 feet above the ground), and most of the time, the sensor was far from the hotspot (more than 25 feet)
Flex Sensor	27	419	5455	The sensor was placed installed on a shoring post (~ 3 feet above the ground), and most of the time, the sensor was far from the hotspot (more than 25 feet)

As shown in Table 4.8, in the field implementation, for the sensor node (temperature/humidity sensor) that was close to the hotspot (less than 3 feet), the average transmission time was 68 seconds (~ 1 minute), with a maximum time of 1688 seconds (~ 30 minutes). However, for the sensor nodes (ultrasonic sensor and flex sensor) that were fairly far from the hotspot, more than 25 feet away, the average transmission time was more than 6 minutes, with a maximum time of 5455 seconds (~ 1.5 hours). Clearly, the distances between the sensor nodes and the hotspot, and the elevation of the sensor nodes, play a significant role in data transmission. A more reliable wireless network method that provides stable connection and coverage on a construction site, and a web host or other data visualization platforms with a broader bandwidth for data transmission, are expected in future studies and implementations.

4.8.2.4 Other Considerations

The accuracy of the ultrasonic sensor used could be further improved by using an external temperature sensor provided by the manufacturer (MaxBotix, 2014). The external sensor would provide the most accurate temperature compensation by placing the external temperature sensor closer to the center of the acoustic ranging path, i.e., in the middle between the sensor and the ground. Also, it was noticed that in the collected distance data, some of the data are outliers – the reflected displacements by such data are unrealistic. These outliers may be a result of the wide beam pattern of the sensor itself that fails to reject side objects. As ultrasound can be easily distorted by the reflected signals caused by nearby metal objects (Zhang et al., 2017). Moreover, during concrete placement, when workers noticed that poured concrete leaked to the ground through gaps between sheathing panels, they walked under the elevated formwork and sprayed the leakage away from the ground. The workers' movements and operations may also have impacted the sensor readings. Therefore, a more accurate, sophisticated, expensive, outdoor-friendly sensor with a narrow beam pattern that integrates with temperature compensation could be chosen for the proposed application. Future work could be conducted to evaluate the developed monitoring tool in assessing the structural behavior of formwork components during concrete placement on different construction sites and under varying environmental conditions, and to report the accuracy level of the obtained results at a given confidence interval (e.g., standard deviation, root mean square (RMS) values, etc.) to facilitate future field usage and implementation.

Furthermore, data privacy and security should be considered for WSN and IoT applications, especially for applications that address safety and health issues, to prevent possible cyber-attacks that target the network and/or the sensor nodes (Kavitha and Sridharan, 2010). Use of encryption and cryptographic authentication is one commonly used approach to ensure the reliability of the network and the security of the sensed data. However, authentication needs additional power and network bandwidth (Kavitha and Sridharan, 2010), which requires further investigation.

4.9 Conclusions and Future Work

Concrete construction is still associated with high numbers of injuries and fatalities, especially during the placement of concrete. Current practice related to formwork monitoring requires considerable human effort, and is dependent on subjective judgment. Technology-based approaches may help in facilitating data acquisition for the monitoring purpose in an efficient, accurate, and safe manner. However, evaluating and selecting appropriate technologies is a critical matter for decision-markers. With a variety of technologies, multiple criteria that often involve conflicts, and vagueness in assessment information, it is very difficult for decision-makers to make the optimal decision. The study proposes to use the fuzzy AHP method for technology selection decisions involving MCDM problems with vague evaluation information. The exploratory study demonstrates how to use the fuzzy AHP method to solve the technology selection problem for the task of monitoring concrete formwork during placement. Through a hypothetical case scenario, ten technology selection criteria, and three potential alternatives are assessed. As a result, the sensor network system is the most preferable technology for application to concrete formwork. Although the result may differ depending on applications, selection criteria, and perspectives from experts, the output shows that the fuzzy AHP method can be a helpful technique for management personnel when assessing the relative importance of selection criteria and technology alternatives.

In addition, a real-time WSN monitoring system for concrete formwork was developed based on the technology selection result. Taking advantage of commercially available sensors and microcontrollers, as well as open-source software, the structural behavior of a horizontal formwork component and a vertical formwork component were tracked throughout the course of concrete pouring. Through a wireless network, the data acquired by the sensors were then transmitted to an IoT website where formwork inspector(s) or other parties of interest could easily access the data via mobile or web-based platforms wherever they are located. The proposed formwork monitoring system was tested on a construction site during concrete placement. Preliminary results show that the proposed system potentially benefits the task of formwork monitoring in several aspects. Firstly, it improves the formwork monitoring quality by delivering objective measurements of the structural behavior of the selected formwork components in an efficient manner. Secondly, it allows real-time data acquisition and visualization and facilitates multi-party collaboration during construction operations. Thirdly, it further ensures the safety of the formwork inspector(s) because there is no need for the inspector(s) to be present and close to the formwork components to check their status during concrete placement, exposing them to potentially dangerous conditions. Lastly, the data acquired by the sensors can be used to determine structural stability by comparing the data to allowable limits to determine the safety of the operation.

The selected and developed technology solution for monitoring the performance of formwork is expected to improve monitoring quality and help ensure the safety of both formwork inspector(s) and construction workers. Future studies are needed to apply, improve and validate the proposed technology selection and monitoring tool. For instance, studies could be conducted to obtain precise and straightforward relative ratings in terms of the importance of criteria and the preference of technologies from the decision-makers' perspectives when selecting the best technology for the task of formwork monitoring, or other construction operations. Ways to incorporate real-time data interpretation (e.g., whether the deformation of a structural member exceeds its maximum allowable limit) need to be further explored, so that an early hazard warning could be triggered automatically for timely corrections and responses to avoid potential structural failures, and to ensure the safety of on-site workers. For applications that require monitoring the performance of multiple formwork components, a system that integrates BIM with real-time data from the WSN system could be developed to enhance the monitoring quality and digital experience. An improved version of the developed monitoring system may also be applied to other temporary structures (e.g., scaffolding) and permanent structures – further investigation could be conducted to verify the applicability and workability of the system, and investigate what features need to be modified or improved.

5. CONCLUSIONS, LIMITATIONS, AND RECOMMENDATIONS

The overarching goal of this dissertation was to advance the body of knowledge and make practical contributions to the integration of temporary structures with advanced technologies, mainly through the identification of the desires and needs of adopting technologies in temporary structures, and the development of tools to improve the quality of temporary structures in the design and construction phases of a construction project.

To attain the research goal, the following research questions were developed to guide the development and outcomes of the study:

(1) What are the current methods used in the design, inspection, and monitoring processes of temporary structures with respect to the level of attention received compared to that of permanent structures? Where are the needed areas of improvement?

(2) What are design and construction professionals' perspectives on adopting innovative technologies in support of designing and monitoring temporary structures?

(3) To improve design quality, what features need to be included in the design tool? How can the features be incorporated in the design tool?

(4) What technologies have been used to monitor the structural health of permanent structures? What are the technology selection criteria that are applicable to select an appropriate technology for temporary structure control and monitoring? What is the relative importance of the identified technology selection criteria? Can the technologies also be used for temporary structures?

(5) To improve onsite inspection and monitoring quality, what method can be used to support decision-making when selecting an appropriate technology given that there are a variety of options? Can the selected technology be useful in monitoring performance?

To answer the abovementioned research questions, fulfill the research objectives, and reach the research goal, both qualitative and quantitative research methods were used in three manuscripts. The methods implemented, main conclusions, along with the research limitations in the three manuscripts are summarized below. Finally, the overall conclusions and contributions of the entire research study are discussed, as well as recommendations for future research.

5.1 Manuscript #1

The first manuscript was designed to answer research question #1 related to current practices associated with temporary structures and needed areas of improvement, research question #2 about the desires and needs to adopt advanced technologies on temporary structures, the former parts of the research question #3 regarding the design features to be incorporated to improve the design of temporary structures, as well as research question #4 related to the applicable technologies for temporary structure control and monitoring and technology selection criteria. The specific research objectives of the manuscript were to:

(1) Investigate the current practices of designing and monitoring temporary structures and identify areas for improvement;
(2) Investigate design and construction professionals' perspectives of using advanced technologies for temporary structures; and
(3) Identify potential technologies that could be used to improve the performance of temporary structures.

To achieve the listed objectives, the research conducted a literature review on the topic followed by a survey that solicited input from both design and construction professionals who have worked with temporary structures and have a basic understanding of construction technology. The main conclusions drawn from 46 valid responses to the survey are:

(1) When compared to permanent structures, the industry currently pays less attention to temporary structures, especially during the design and planning

phases. Additional care should be paid to temporary structures in the design and construction phases of a construction project.

(2) Industry design and construction professionals generally hold positive attitudes toward applying construction innovations on temporary structures to improve the design quality and structural health when they are in use.

(3) The identified leading causes of temporary structure failures are procedural causes (e.g., insufficient control and monitoring during operations, inadequate review of designs, etc.)

(4) During the design phase, technologies such as BIM could offer better ways to identify safety hazards, facilitate effective communications with multiple stakeholders (e.g., designers, constructors, etc.), identify design deficiencies, and incorporate safety considerations.

(5) During the construction phase, the frequency and accuracy of current manual inspection and monitoring practices to temporary structures are considered inadequate, and the practices are associated with a high level of interruptions to operations. Frequent inspection and maintenance during operations is viewed as the most promising approach to improve the safety performance of temporary structures. Sensor-based technology, video/photo logs, and laser scanning are considered to have the potential to assist with inspecting and monitoring temporary structures when they are in use.

(6) To select an appropriate technology to perform the inspection and monitoring task for temporary structures, ten technology selection criteria, covering four aspects including performance, interference, cost and practicability, are identified. Based on the analysis with the RII method, whether the technology provides a desirable result, whether it is easy to use and implement, and whether it provides quality data, are the three most important criteria to consider.

While the work presented brings some insights to the deficiencies associated with the current practices in the design, inspection, and monitoring processes of temporary structures, and the desires and needs to adopt advanced technologies on temporary structures, there are several limitations to the work presented in this manuscript. These limitations include:

(1) The results are based on surveys, which are highly dependent on the perceptions of the survey participants, judgement bias exists within the study.
(2) The adopted non-probability sampling techniques introduces selection bias. Survey participants were selected purposefully to form a group of professionals who are familiar with temporary structures and are interested in the technology. Other participants were recruited through sampling networks.
(3) Considering the relatively small sample size (n = 46) and the abovementioned bias, the findings and conclusions drawn from the study could not be used to identify causal relationships and make accurate inferences to a larger population. Further studies are expected to improve the quality (e.g., generalizability) of the research by adopting a mixed or multimethod approach with a larger sample size.

5.2 Manuscript #2

Based on the research findings from Manuscript #1 pertaining to the design and planning phases, the second manuscript aims to explore ways to incorporate safe design procedures and consideration within BIM authoring tools, and enable formwork model automation, with an objective to improve the design and model quality of temporary structures. The second manuscript was designed to answer the latter part of research question #3 related to the incorporation of design features within the formwork design tool to improve the design quality of temporary structures. The type of temporary structure selected was concrete formwork.

The study proposes a framework to incorporate the concrete formwork design process and safety rules with BIM authoring tools for designers when designing and planning temporary structures. A BIM-based plug-in was developed to assist with formwork designs and model generation. The proposed tool was tested on a 3D BIM model to demonstrate the interfaces and workability, and its usefulness and efficiency was verified by formwork professionals using a survey questionnaire. Findings from the survey suggest that the participants held generally positive perceptions of the proposed formwork design and modeling tool, especially regarding its improvements to the design and modeling efficiency, and its ease of use.

While the work presented is a novel tool for designing and modeling concrete formwork components, there are several limitations to the work presented. These limitations are:

(1) The proposed tool was only tested on a prototype BIM model and two examples from the ACI formwork book (ACI, 2014a). The usefulness of the tool was not tested and confirmed with an actual concrete project.

(2) The tool only supports the design of regular-shaped concrete slabs/walls and the use of timber formwork components.

(3) When verifying the workability, usefulness and efficiency of the proposed tool with a survey, the results might be biased because of the adopted nonrandom sampling methods and the small sample size (n = 25). The findings cannot be generalized with high confidence beyond the survey participants.

5.3 Manuscript #3

Manuscript #3 placed a focus on concrete formwork during the construction phase. The third manuscript was designed to answer research question #5 related to technology selection, and to address research question #4 about technology application for temporary structure SHM. Building upon the identified and assessed technology selection criteria in Manuscript #1, the study performs a systematic decision-making analysis using the fuzzy AHP method, through a hypothetical case scenario, to select an appropriate technology from several alternatives to monitor the performance of concrete formwork during the placement of concrete. Based on the selection result, a real-time WSN monitoring system for concrete formwork was developed using commercially available and open-source hardware and software. The proposed monitoring system was tested and verified on a real-world building project during concrete placement. Preliminary results of the experiment show the proposed system is capable of acquiring and visualizing real-time information about the monitored formwork components. Such information could be used to assess structural stability, and to improve the safety of formwork inspectors and construction workers.

Limitations associated with the technology selection process and the proposed monitoring tool include:

(1) The relative importance ratings of the technology selection criteria, and the relative preference ratings for technology alternatives based on the selection criteria, were not obtained from decision-makers and/or expert panels. Judgment bias exists in the presented work of the technology selection process.
(2) The current form of the proposed monitoring tool does not support the assessment of the structural instability conditions in real-time and, therefore, was unable to provide early hazard warnings to contractors for timely responses and corrective actions.
(3) The proposed monitoring system was only tested on one case study project. Therefore, the generalizability of the findings to concrete formwork at large is limited.

5.4 Overall Research Conclusions and Contributions

A key contribution of the present study is that it reinforces the important role of temporary structures in the industry. In addition to focusing on the performance of the permanent structure, careful considerations must also be given to temporary structures during the design and construction phases of a project. The study contributes to the body of knowledge by identifying the needs and desires of industry practitioners with respect to adopting technologies for temporary structures, providing professionals' insights in terms of room for improvement of temporary structures during the design and construction phases, identifying and assessing technology selection criteria for temporary structures inspection and monitoring tasks, as well as creating a rational decision-making process for selecting technology for temporary structures. Researchers could use the findings from the study as a starting point to prompt technology usage for temporary structures, improve formwork design and structural integrity, advance associated design, inspection, and monitoring practices, and improve the safety of the workers who have to work with temporary structures.

The study also makes practical contributions by developing two technology-based tools to enhance technology integration with temporary structures. One tool is a BIM-based tool that provides a streamlined formwork design and modeling process with the consideration of worker safety and health. The other is a WSN monitoring tool that enables real-time data acquisition and visualization for concrete formwork components during the placement of concrete. Researchers could use the information presented in the work to develop advanced tools for the same type of temporary structures, i.e., concrete formwork or other commonly-used types of temporary structures. Also, design and construction practitioners could utilize the proposed tools in their design, planning, inspection and monitoring practices for concrete formwork.

5.5 Recommendations for Future Research

The identification of needs and desires of technology adoption for temporary structures is expected to set the foundation for subsequent and future work on improving worker safety and health associated with temporary structures utilizing the benefits offered by technological improvements. Further studies are needed to confirm the desires and needs, and investigate enablers and barriers of technology adoption for temporary structures within different types and sizes of construction projects.

As for the proposed tools, they were only tested on limited case studies. Future studies are anticipated to apply them in different construction projects for a better understanding of the performance of the tools, and practical limitations. In addition, the current form of the proposed tools is subject to many technical limitations, which need to be further improved. For the BIM-based formwork design and model tool, it could be integrated with a database that provides design parameters for prefabricated and modularized formwork systems to extend the scope of the tool, not limiting it to timber formwork systems. Functions such as shoring/reshoring analysis, detailed quantity take-offs, cost estimates, and constructability analysis could be incorporated so that the proposed tool could address additional issues of concern in the planning phase.

As for the developed WSN formwork monitoring tool, future studies could be performed to enable the real-time analysis and early hazard warning features to fully realize the benefits offered by the proposed monitoring tool. With the help of BIM, RFID, and other technologies, it is possible to develop an integrated system that could be used throughout the entire life cycle of a concrete formwork system.

Lastly, as listed in Table 1.1, the technology-based solutions in previous studies often lack detailed cost-benefit analysis which may influence the transition from research into practice. Future studies could be performed to build business cases to investigate the long-term impacts of adopting technologies for temporary structures on project cost, safety, quality and productivity, as well as identifying implementation challenges.

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APPENDICES

Appendix I - Survey Questionnaire:

Temporary Structures and Innovative Technology

Explanation of Research Study

Project Name: Temporary Structures and Innovative Technology

Principal Investigator: John A. Gambatese / Oregon State University

Student Investigator: Ziyu Jin / Oregon State University

Why am I being invited to take part in this study?

You are invited to take part in this research study as you are identified as having extensive knowledge of construction projects, associated with a construction industry organization, and/or experience in this discipline. This research project is being conducted by a student for the completion of a thesis or dissertation.

What is the purpose of this study?

Design personnel generally pay more attention to ensuring the safety of permanent structures than that of temporary structures. However, a great deal of accidents are due to failures of temporary structures. Ways to minimize design errors and to improve quality control during construction operations are needed. The purpose of this study is to investigate the current practices of temporary structures during the design and construction phases, to explore the potential for using innovative technologies (e.g., laser scanning, sensor-based technology, image-based technology) in support of design and monitoring of temporary structures, and to solicit professionals' opinions on a developed design tool for temporary structures. It is expected the results from the survey can be used to identify the optimal method to control and monitor temporary structures when they are in use, and to verify the effectiveness of the proposed tool.

What will happen during this study and how long will it take?

In the survey, you will be asked to express your opinion and share your experience related to the design and use of temporary structures, and the application of innovative technologies in the construction industry. In addition, you will be asked to read a description document or watch a demonstration video about the proposed design tool, and express your opinion related to the developed design tool. It is expected that the survey will take approximately 15 minutes to complete.

What are the risks of this study to the participants?

Accidental disclosure of the written responses: None. Personal identities are not required to complete the survey, and personal identification information will not be asked. Thus, survey responses cannot be traced to individual companies or people. Internet: The security and confidentiality of information collected from you online cannot be guaranteed. Information collected online can be intercepted, corrupted, lost, destroyed, arrive late or incomplete, or contain viruses.

What are the benefits of this study to the participants?

There are no direct benefits to you from this study. However, the overall benefit to the industry will be to have further knowledge that can help improve safety in the construction industry. Oregon State University might also benefit if the study attracts funding for additional research from companies, organizations, and/or government agencies.

Do I have a choice to be in the study?

Participation in the study is voluntary. Participants may refuse to answer any questions and/or may withdraw from the study at any time.

What if I have questions?

Participants are encouraged to ask any questions at any time about the study and its procedures, or his/her rights as a participant. The Investigators' names and contact information are included below so that the participant may ask questions and report any study-related problems.

- John Gambatese, School of Civil and Construction Engineering, Oregon State University, 101 Kearney Hall, Corvallis, OR 97331, john.gambatese@oregonstate.edu

- Ziyu Jin, School of Civil and Construction Engineering, Oregon State University, 101 Kearney Hall, Corvallis, OR 97331, jinzi@oregonstate.edu

If you have any questions about your rights or welfare as a participant, please contact the Oregon State University Institutional Review Board (IRB) Office at 541-737-8008 or by e-mail at irb@oregonstate.edu.

Acknowledgement:

By continuing the survey, I have read the above description of the research. If I had questions or would like additional information, I contacted the researchers and had all of my questions answered to my satisfaction. I agree to voluntarily participate in this research. By answering the survey questions and responding to this survey, I affirm that I have read the above information, agree to participate in the research, and am at least 18 years of age or older.

Survey Questions for Contractors and Designers

Part 1: Background Information

Q1. Have you ever worked with temporary structures (e.g., formwork, shoring, scaffolding) on a project?

- Yes
- No

Q2. What type of temporary structures are you familiar with? Please select all that apply.

- Concrete formwork
- Scaffolding
- Shoring
- Earth-retaining structures
- Other, please specify: ____________________
- None

Q3. How many years of industry experience do you have?

- Less than 1 year
- 1 – 5 years
- 5 – 10 years
- 10 – 20 years
- More than 20 years

Q4. Please select the type of company that you work for:

- General Contractor
- Subcontractor
- Architecture
- Structural Engineering
- Research/academic
- Other, please specify: ____________________

Q5. What is your job title?

- Project Engineer
- Project Manager
- Project Architect
- Superintendent
- President
- Other, please specify: ____________________

Part 1: General Temporary Structure Questions

Q6. How much attention does the industry currently give to temporary structures compared to the permanent structure during the **design** phase of a project?

- Much less
- Slightly less
- About the same
- Slightly more
- Much more
- I do not know

Q7. How much attention does the industry currently give to temporary structures compared to the permanent structure during the **construction** phase of a project?

- Much less
- Slightly less
- About the same
- Slightly more
- Much more
- I do not know

Q8. Please indicate your agreement/disagreement with the following statement: More attention should be given to temporary structures during the **design** phase?

- Strongly agree
- Somewhat agree

- Neither agree nor disagree
- Somewhat disagree
- Strongly disagree
- I do not know

Q9. Please indicate your agreement/disagreement with the following statement: More attention should be given to temporary structures during the **construction** phase?

- Strongly agree
- Somewhat agree
- Neither agree nor disagree
- Somewhat disagree
- Strongly disagree
- I do not know

Q10. Based on your experience, what are the leading causes of temporary structure failures? Please select all that apply.

- Design errors
- Improper assembly/removal
- Insufficient control and monitoring during operations
- Lack of communications among the permanent structure's designer, general contractor, and subcontractor
- Unstable foundation
- Heavy construction loads (overloaded by materials, equipment, personnel)
- Bad weather
- Other, please specify: ____________________

Q11. Based on your experience, how would you rate the quality of each of the following current practices in controlling and monitoring temporary structures on site? (1 indicates extremely poor; 5 indicates excellent).

- Frequency of inspections _________
- Level of accuracy of the inspections _________

- Interruption to operations __________
- Cost of inspections __________
- Time required to perform inspections __________

<u>Part 1: Questions related to Methods of Improvement</u>

Q12. Based on your knowledge and experience, what opportunities are there to improve **safety** performance of temporary structures? Please select all that apply.

- Improved regulations and standards
- More education on designing temporary structures
- Better worker training
- Frequent inspection and maintenance during operations
- Use of innovative technology (BIM, drones, sensor-based technology, laser scanning, etc.) to design or monitor temporary structures
- Other, please specify: ______________________

Q13. In your opinion, for which of the following activities do technologies such as BIM, laser scanning, etc. provide assistance when **designing** temporary structures? Please select all that apply.

- Design deficiencies identification (through visualization and simulation)
- Safety hazards (e.g., falls) identification
- Design modifications based on safety considerations
- Effectively communication with contractor and other stakeholders
- Other, please specify: ______________________

Q14. In your opinion, when selecting technologies to control and monitor temporary structures on site, how important are the following aspects of the technology?

Aspects of Technologies	Not at all important	Slightly important	Moderately important	Very important	Extremely important
	1	2	3	4	5
Meets required need(s); has required features					
Providing desirable result (level of accuracy, robustness, etc.)					
Easy to use and implement					
Less disruption to operations					
Quality of data (reliability)					
Cost of purchase					
Cost of installation and maintenance					
Time efficiency in data acquisition					
Time efficiency in data processing and interpretation					
Training requirements					
Other, please specify: _______					

Q15. Please share any opinions that you may have for improving safety performance of temporary structures: ____.

Part 1: Questions related to Technology

Q16. Have you encountered projects that use any of the following technologies to improve site safety in general, not necessarily specifically related to temporary structures? Please select all that apply, and indicate what the technologies were used for.

- Laser scanning ______________
- BIM/Virtual Design and Construction (Virtual Reality, Augmented Reality) ______________
- Drones (Unmanned aerial vehicles (UAVs)) ______________
- Video/Photo logs ______________
- Sensor-based Technology ______________
- Global Positioning System (GPS) ______________
- Radio-frequency identification (RFID) ______________
- Other(s), please specify ______________

Q17. What technologies do you think might be helpful to improve the performance of temporary structures? Please select all that apply.

- Laser scanning
- BIM/Virtual Design and Construction (Virtual Reality, Augmented Reality)
- Drones (Unmanned aerial vehicles (UAVs))
- Video/Photo logs
- Sensor-based Technology
- Global Positioning System (GPS)
- Radio-frequency identification (RFID)
- Other(s), please specify ______________

Part 2: New Section (Questions related to the Developed Design Tool)

Q18. Do you have experience working with BIM related software?

- Yes
- No

Q19. The research team recently developed a BIM-based tool (a Revit plug-in) for designing and modeling formwork systems for concrete slabs and walls. You can find details about the tool by reading through a description document (https://drive.google.com/file/d/1wmWVL8dnu6SIR1YdmlvXswiEHHggtyr_/view?usp=sharing), or watching a demonstration video (https://youtu.be/_Jo2fg5ghEg). After reviewing the description document or watching the demonstration video, please rate the degree to which you agree or disagree with each of the following statements related to the developed Revit plug-in.

	Strongly disagree	**Somewhat disagree**	**Neither agree or disagree**	**Somewhat agree**	**Strongly agree**
	1	**2**	**3**	**4**	**5**
The plug-in is easy to use and implement.					
The plug-in provides adequate accuracy.					
The plug-in saves time when designing formwork components.					
The plug-in saves time when modeling formwork components.					
The plug-in is a labor-saving tool when designing and modeling formwork systems.					
The plug-in has potential to improve design and model quality.					
The plug-in has potential to improve worker health and safety.					

Q20. Please share any comments or suggestions that you may have for the developed Revit plug-in:

____

Once again, we are extremely grateful for your participation in this survey, your honest information, and your thoughtful suggestions. Your responses are vital for helping to enhance safety related to temporary structures. If you have any questions or want to learn more about our research, please feel free to reach us at: jinzi@oregonstate.edu, or john.gambatese@oregonstate.edu. Thanks again!

Appendix II - Revit Formwork API Introduction Document

Design for Concrete Formwork
Introduction & Tutorial

This document presents the main features of a BIM-based concrete formwork design tool. The current version of the tool is developed in Visual Studio 2019 using C# language in the .NET Framework (version 4.7), and implemented in Autodesk Revit 2020.

The document is organized in the following order.

- About Design for Concrete Formwork Plug-in
- Introduction and User Interface
- Step-by-Step Examples
- For a Concrete Slab
- For a Concrete Wall
- Demonstration Video

About Design for Concrete Formwork Plug-in

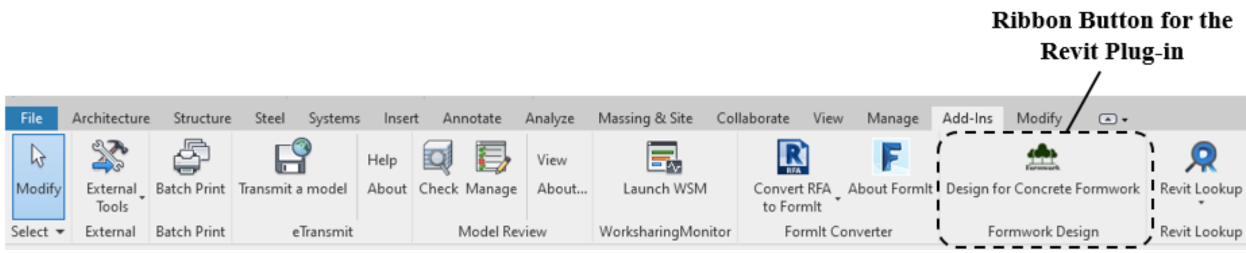
Design for Concrete Formwork is a Revit Application Programming Interface (API) that allows you to **design, analyze, and model formwork systems for concrete walls and slabs**. The API provides a simple and fast approach of conducting structural analysis based on design procedures recommended by the American Concrete Institute (ACI), providing safety and health suggestions related to fall protection and material handling, and generating models in Revit.

<u>Highlights of the Proposed Revit Plug-in:</u>

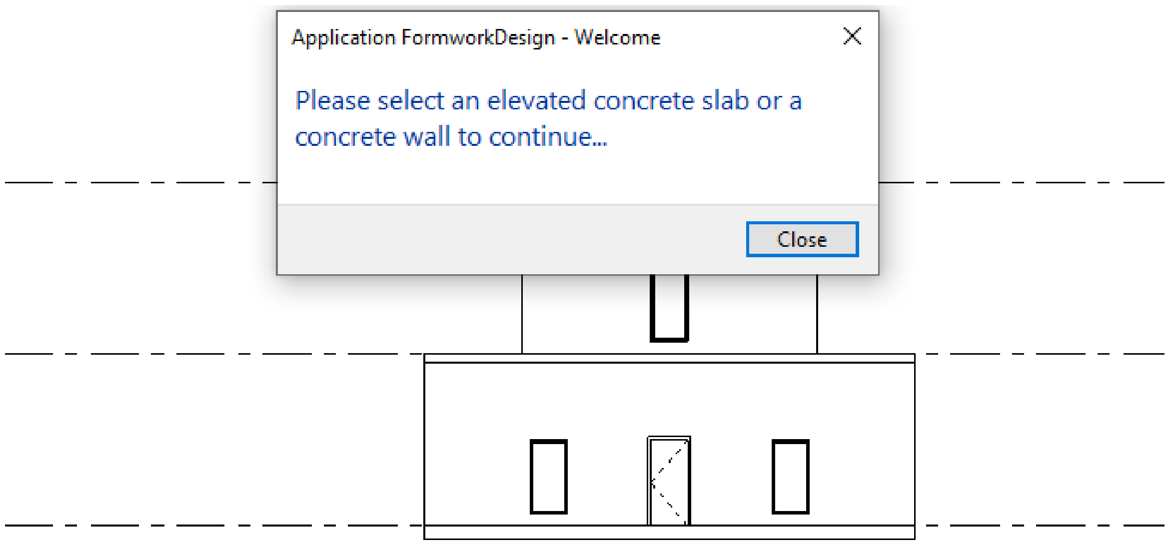
- Design and model formwork system for a concrete slab and wall in Revit less than 10 minutes.
- Guided systematic approach to design formwork systems for concrete slabs and walls.
- No need to check design tables, properties of timber members, and adjustment factors.
- Incorporate with safety and health suggestions in terms of fall protection and material handling that can be used during the planning phase.
- The generated model has a wide range of applications, including but not limited to design visualization and simulation, quantity takeoff, and constructability analysis.

Introduction and User Interface

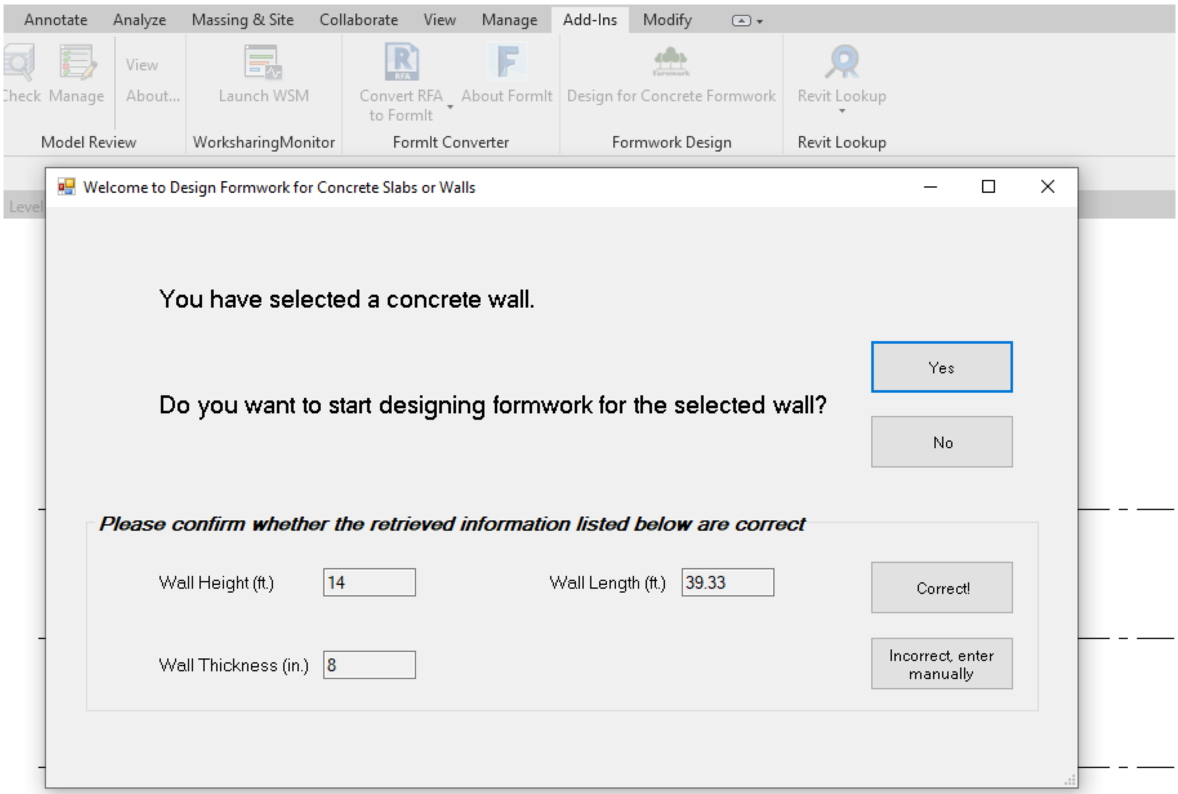
1. Opening the API by clicking the ribbon button for the Revit plug-in



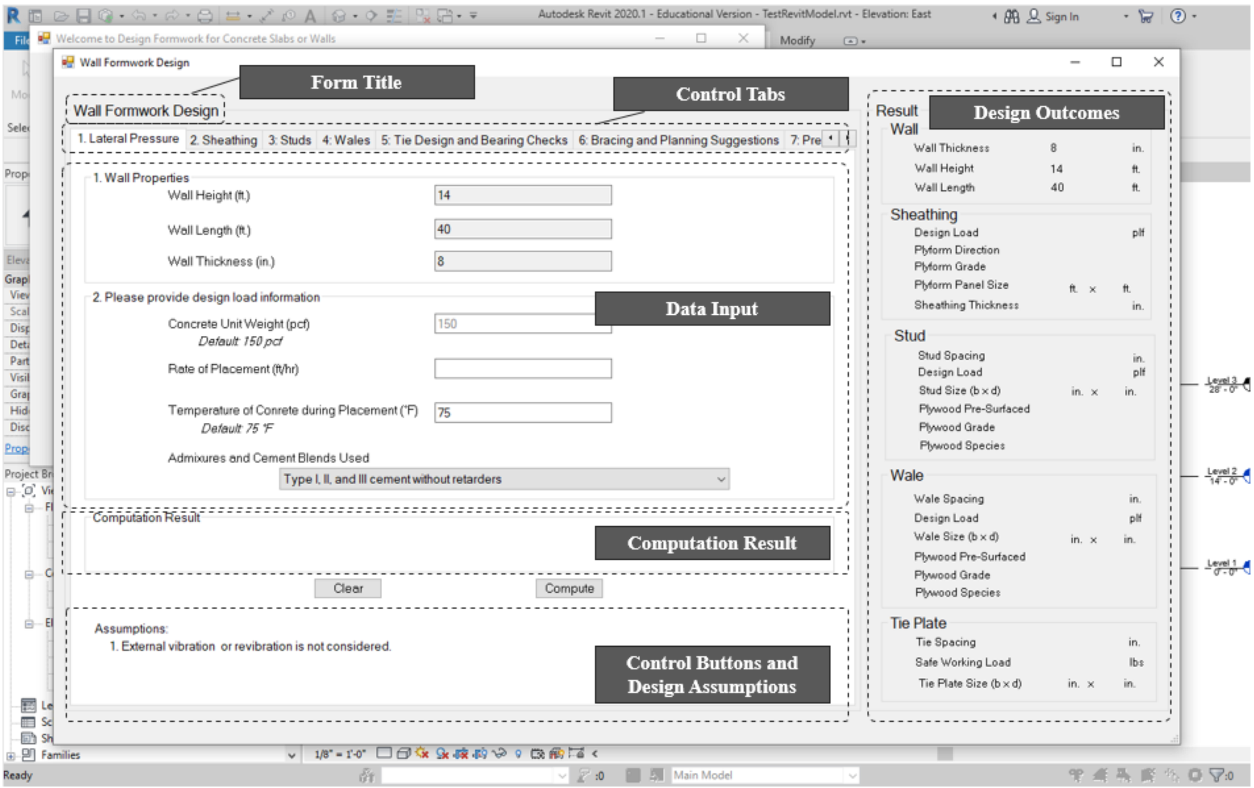
2. A pop-up welcome message in Revit is shown to remind user to select either a concrete wall or a slab



3. After making selection on a wall or a slab (in this case, a wall), a window form appears to retrieve (by clicking "Yes") and show basic information (e.g., wall/slab thickness) for the selected item.



4. The main form provides a set of tools that are used to navigate and run the design process, as well as areas to display design outcomes. The main form consists of the form title, the control tabs, the control buttons, and areas for data input, and showing computation result and design outcomes.



Form Title: shows whether the form displayed is for wall formwork design or slab formwork design.

Control Tabs: provides a guidance to the design procedures of formwork systems, and enables users to switch among different design tasks. In the current version, the tabs included in the current version for slab and wall formwork design are listed in the table below.

Tab #	Slab Formwork Design	Wall Formwork Design
1	Design Load	Lateral Pressure
2	Sheathing	Sheathing
3	Joists	Studs
4	Stringers	Wales
5	Shores	Tie Design and Bearing Checks
6	Bearing Checks	Bracing and Planning Suggestions
7	Bracing and Planning Suggestions	Preview and Model
8	Preview and Model	

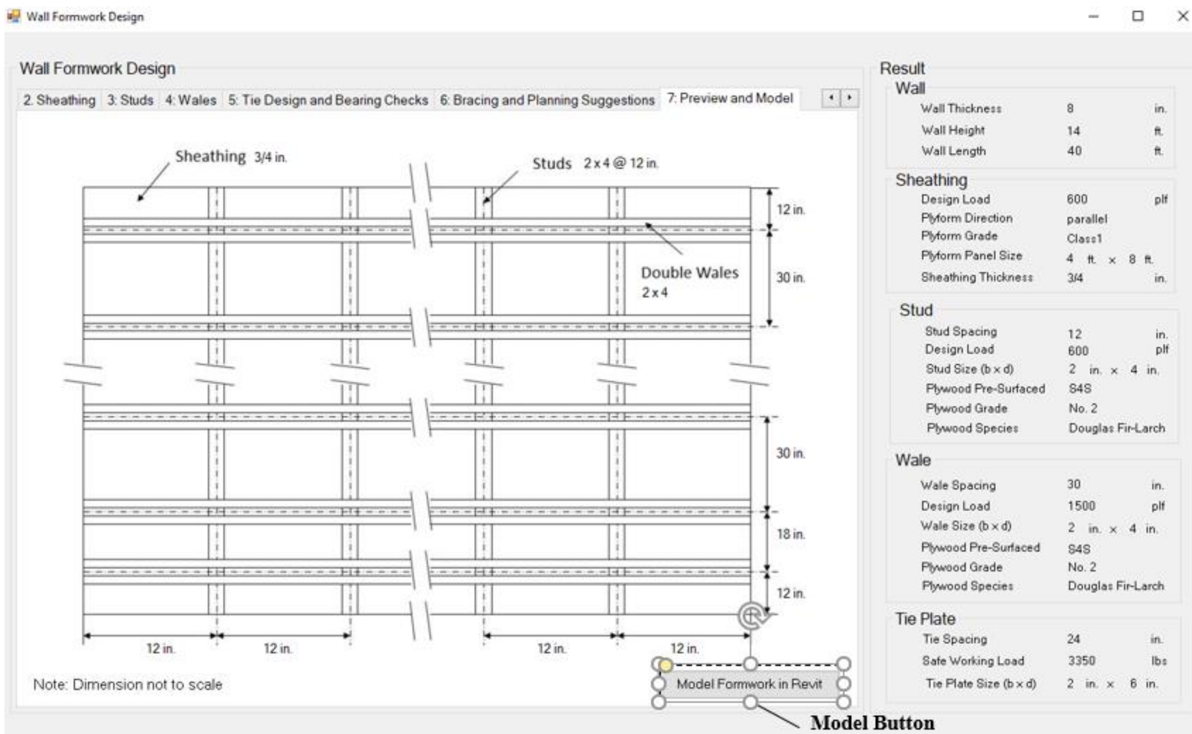
Data Input: allows users to select applicable design conditions from drop-down lists or manually enter the required information.

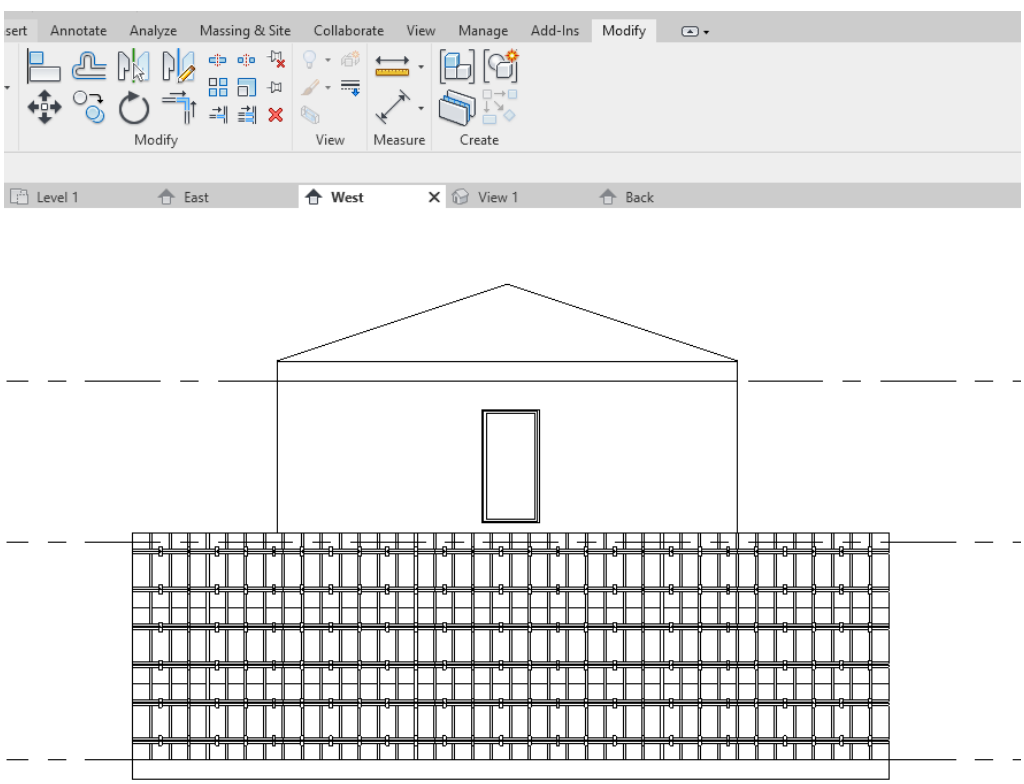
Computation Result: provides recommended design values for users to consider.

Control Buttons and Design Assumptions: provides buttons to reset data input, conduct analysis, confirm a design decision, and model design features, and displays assumptions used in the design process.

Design Outcomes: presents user's design decisions for formwork components.

5. After the design process is completed, users can preview the design and click "Model Formwork in Revit" to model the designed components in Revit.





Step-by-Step Examples

Two step-by-step examples (one for designing slab form, and the other one for designing wall form) are illustrated in this document to demonstrate the design process of the proposed plug-in, and to verify its applicability and correctness. The formwork design examples from ACI *Formwork for Concrete* (Johnston, 2014) are served as the ground truth: Example 7.4 for slab form design and Example 7.2 for wall form design. In addition, a 3D model of a simple two-story building was created in Revit to test the proposed Revit plug-in. Minor adjustments to the design assumptions from the original examples (e.g., ceiling height, sheathing panel size, etc.) are made so that the two examples could be demonstrated within the same Revit model.

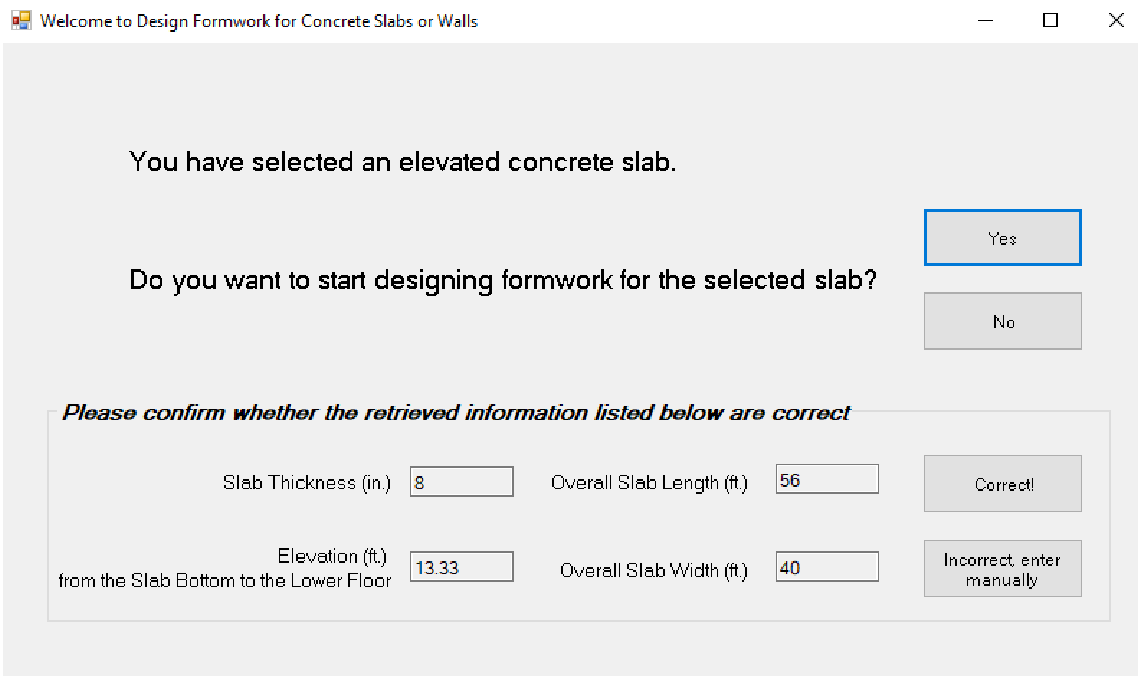
For a Concrete Slab

The **design assumptions** for the selected concrete slab (56 ft. x 40 ft.) are listed as follows.

- 8 in. thick, normal-weight concrete slab;
- Ceiling height is 14 ft.;
- ¾-in Structural I, B-B Plyform sheathing (4 ft. x 8 ft. panels);
- Construction grade, Douglas Fir-Larch, S4S framing members;
- Span length for stringer and shoring will be 5 ft.;
- The estimated weight of forms is 8 psf;
- Forms will be substantial reused (no adjustment needed for short-term load);
- Job conditions are such that the wood joists and stringers will not be subject to wet service;
- Deflection of framing members is limited to 1/360 times the span length

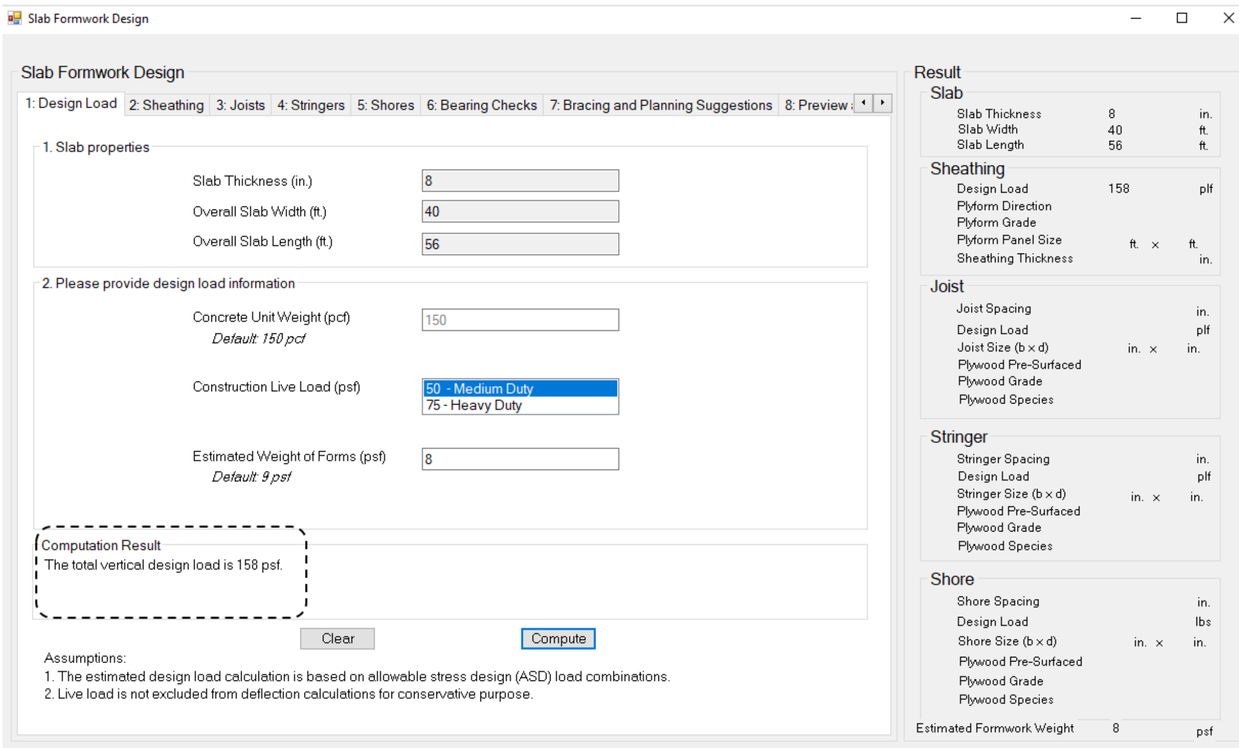
Step 1: Open the plug-in, and the user makes a selection from the Revit model for a concrete slab;

Step 2: The plug-in extracts/computes the parameters of the selected slab (thickness, length, width, elevation from the bottom of the slab to the lower floor);



Step 3: After the user confirms the retrieved slab information, the main user interface is shown to guide the user through the systematic slab formwork design procedures. After entering/selecting the required and applicable information for calculating design load for the selected slab (concrete unit weight: 150 pcf, medium construction live load, and estimated weight of forms: 8 psf) in **Tab 1 (Design Load)**, the result is shown as follows:

The total vertical design load is 158 psf.



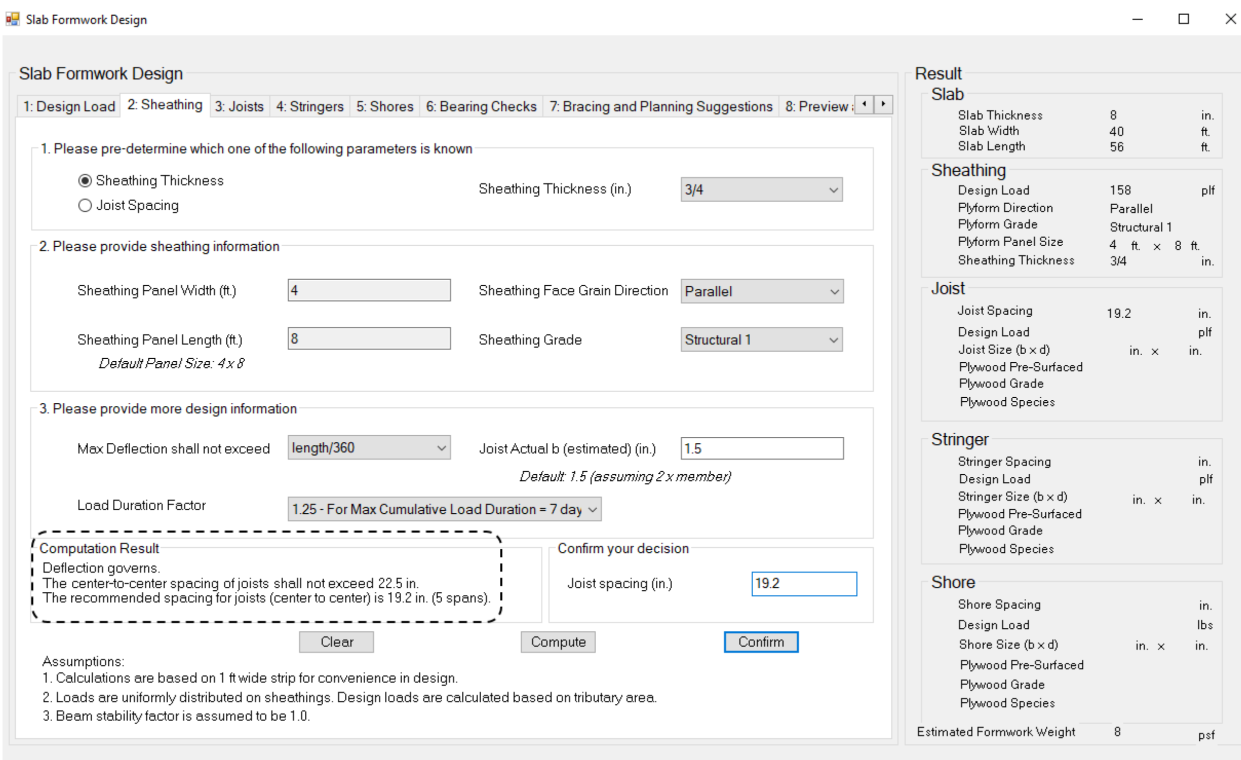
Step 4: In **Tab 2 (Sheathing)**, after entering/selecting the required and applicable information for designing sheathing panels and joist spacing (sheathing thickness: ¾-in, sheathing face grain direction: parallel, sheathing grade: Structural I), the computation result is shown as follows:

Deflection governs.

The center-to-center spacing of joists shall not exceed 22.5 in.

The recommended spacing for joists (center to center) is 19.2 in. (5 spans).

Please note that for the proposed API, to be conservative, live load is considered for vertical deflection, which is slightly different from the original example (Example 7.4 from *ACI Formwork for Concrete*). Therefore, the results presented here are not the same.

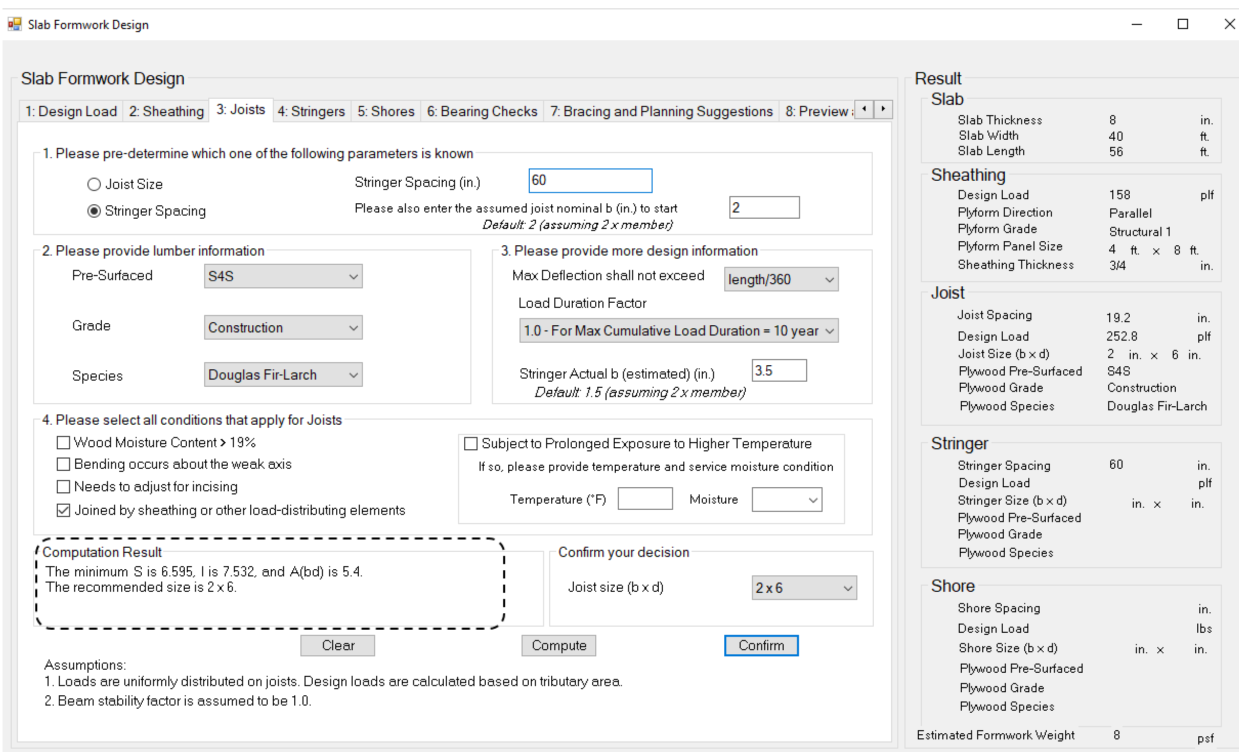


Step 5: In **Tab 3 (Joists)**, after entering/selecting the required and applicable information for designing joists and stringer spacing (stringer spacing: 60 in, joist pre-surfaced: S4S, grade: construction, species: Douglas-Fir-Larch), the computation result for joist size properties is shown as follows:

The minimum S is 6.595, I is 7.532, and A(bd) is 5.4.

The recommended size is 2x6.

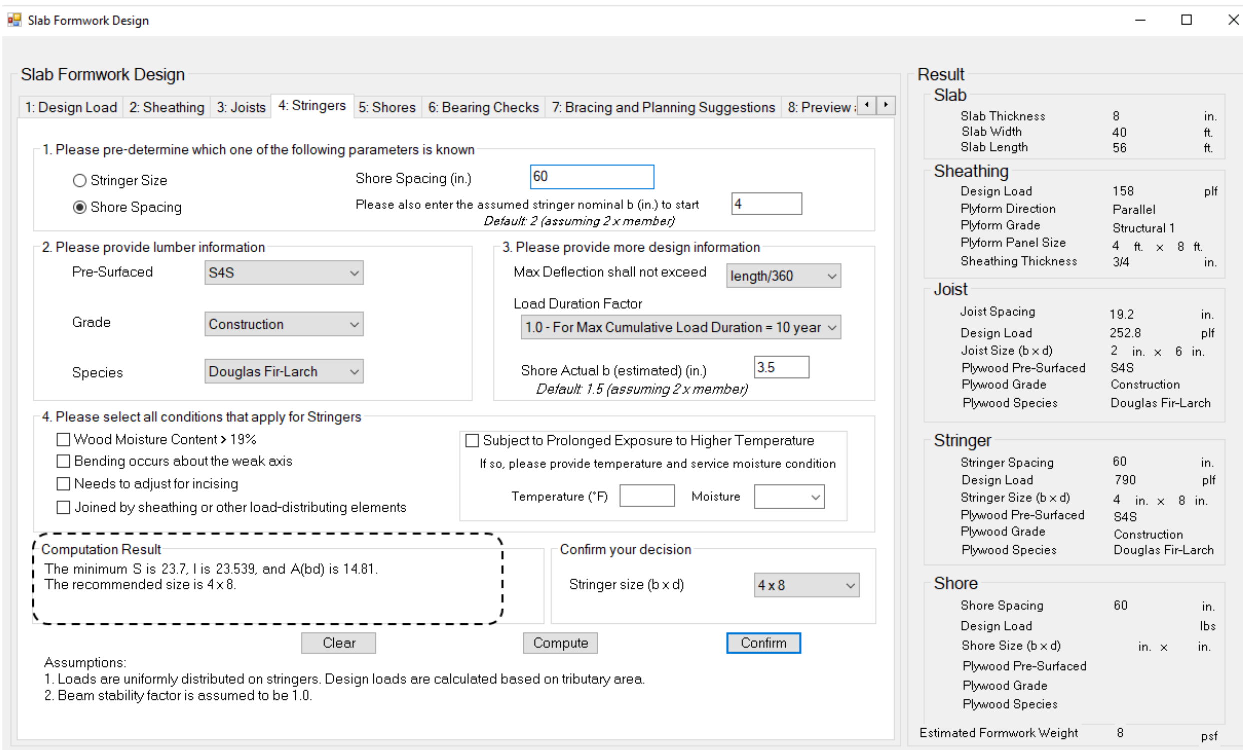
The user can confirm the design decision based on material availability and design preferences.



Step 6: In **Tab 4 (Stringers)**, after entering/selecting the required and applicable information for designing stringers and shore spacing (shore spacing: 60 in, stringer pre-surfaced: S4S, grade: construction, species: Douglas-Fir-Larch), the computation result for stringer size properties is shown as follows:

The minimum S is 23.7, I is 23.539, and A(bd) is 14.81.

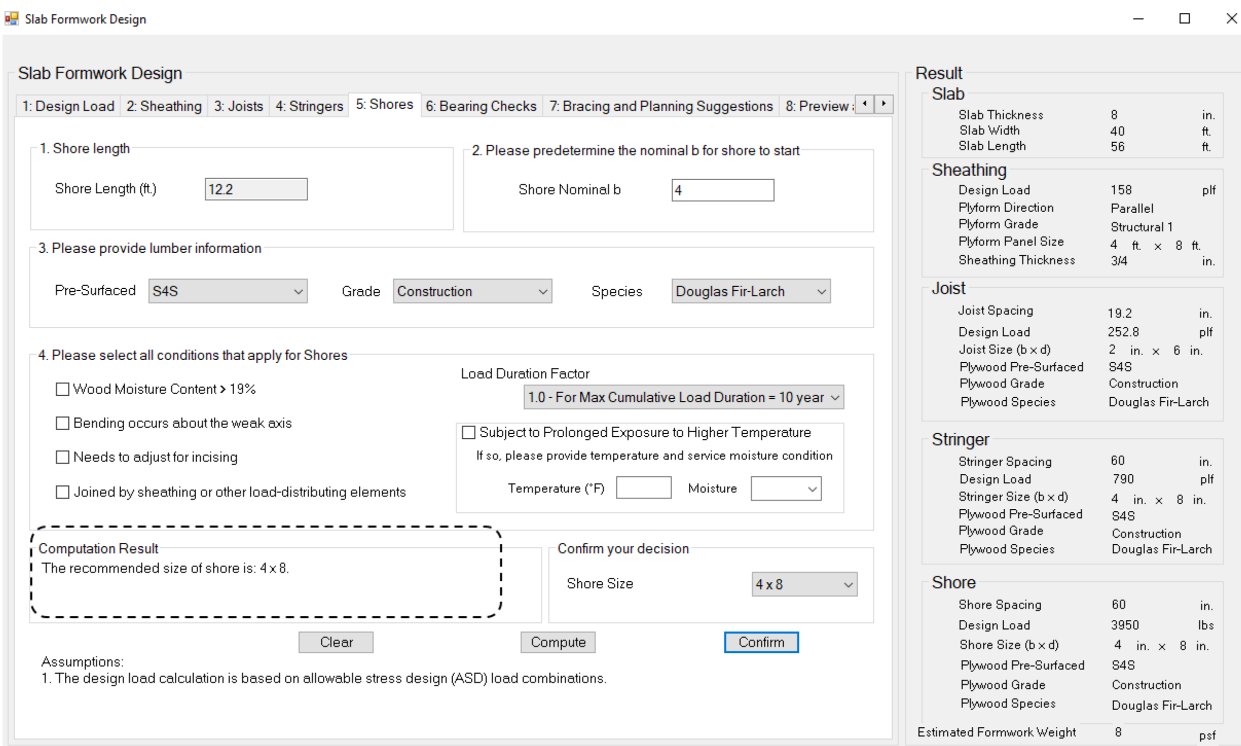
The recommended size is 4x8.



Step 7: In **Tab 5 (Shores)**, after entering/selecting the required and applicable information for designing shores (shore pre-surfaced: S4S, grade: construction, species: Douglas-Fir-Larch), the computation result for shores is shown as follows:

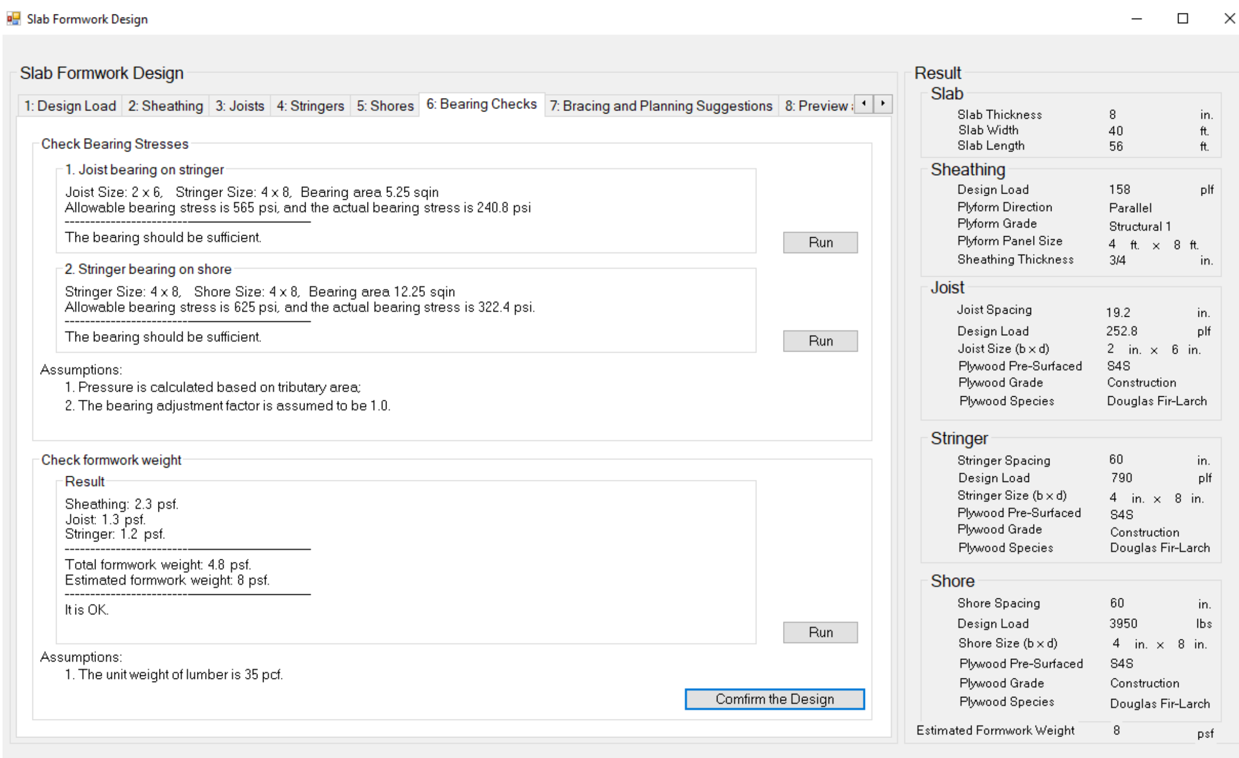
The recommended size is 4x8.

Please note that the ceiling height used (14 ft.) is different from the original example, therefore, the size of shores is not the same.

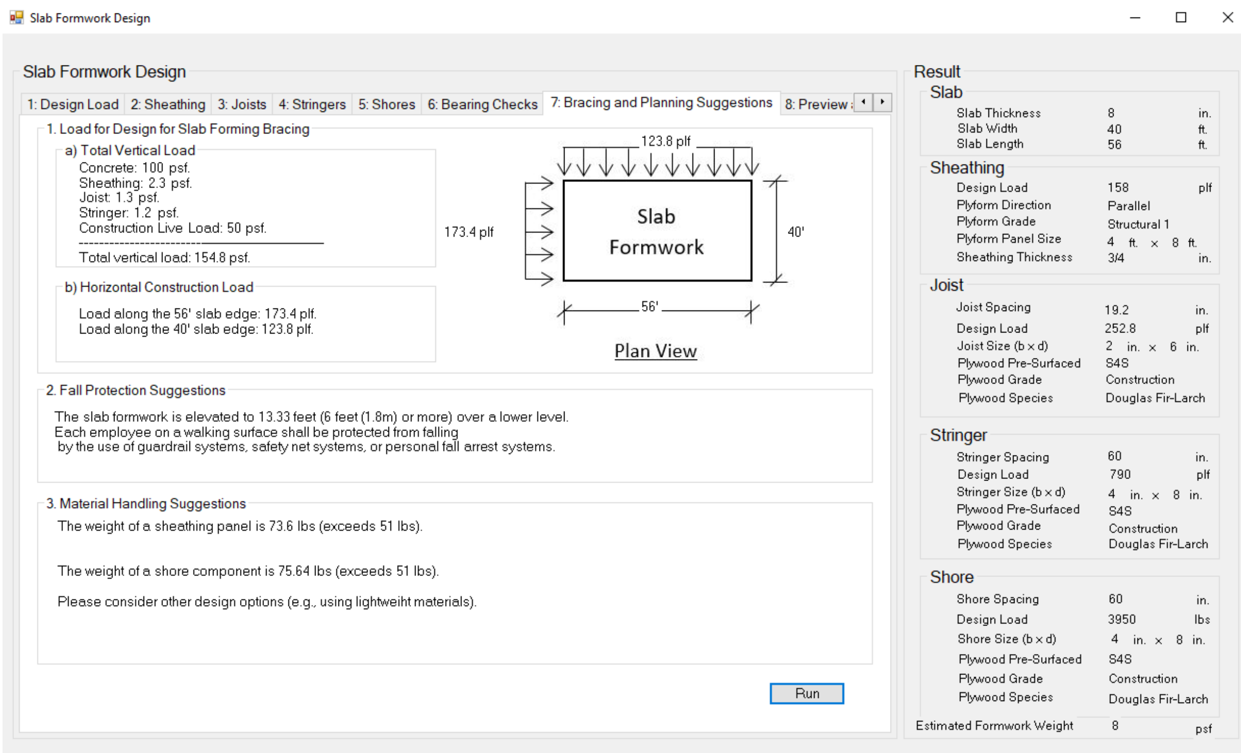


Step 8: In **Tab 6 (Bearing checks)**, the user can check whether bearing stresses (where stringers bear on shores, and where joists bear on stringers) exceed the allowable design stresses, and check whether the weight of the designed form system exceed the estimated weight of forms.

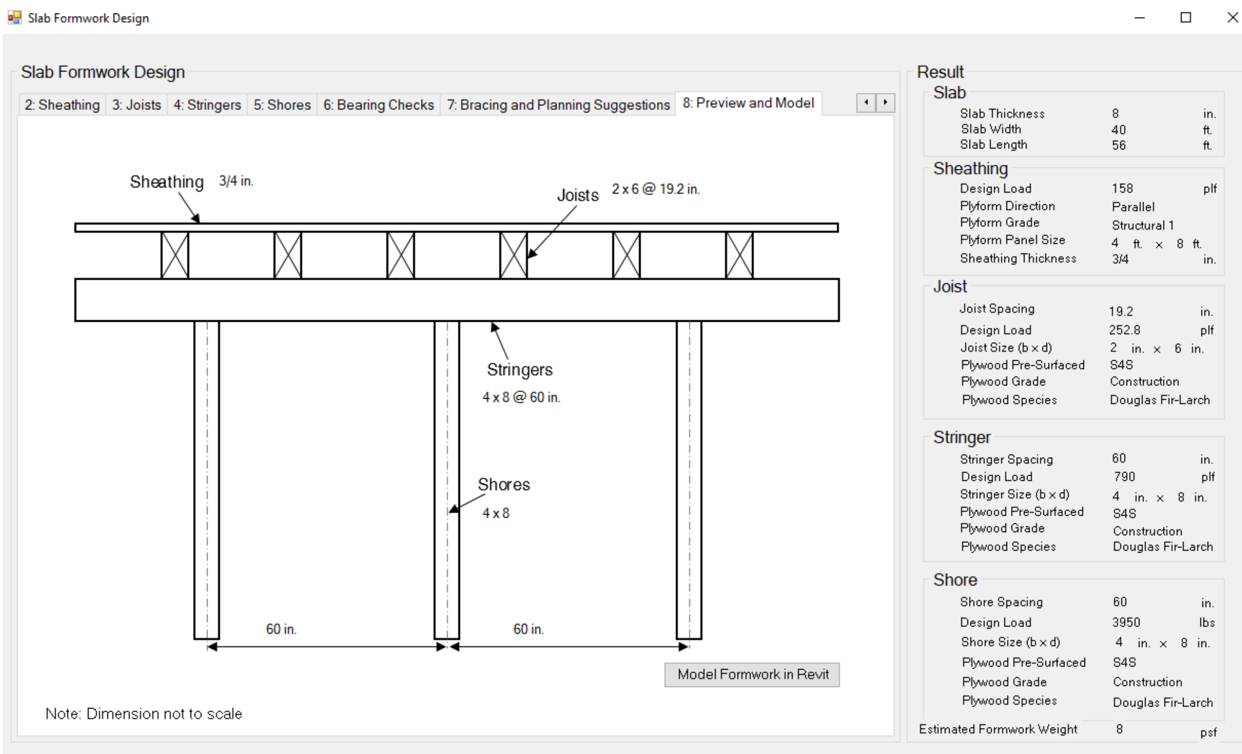
Please note that the plug-in currently does not support the inclusions of head pieces that connect stringers and shores. Therefore, the bearing check between stringers and shores in the current version only consider the contact area between the two members.



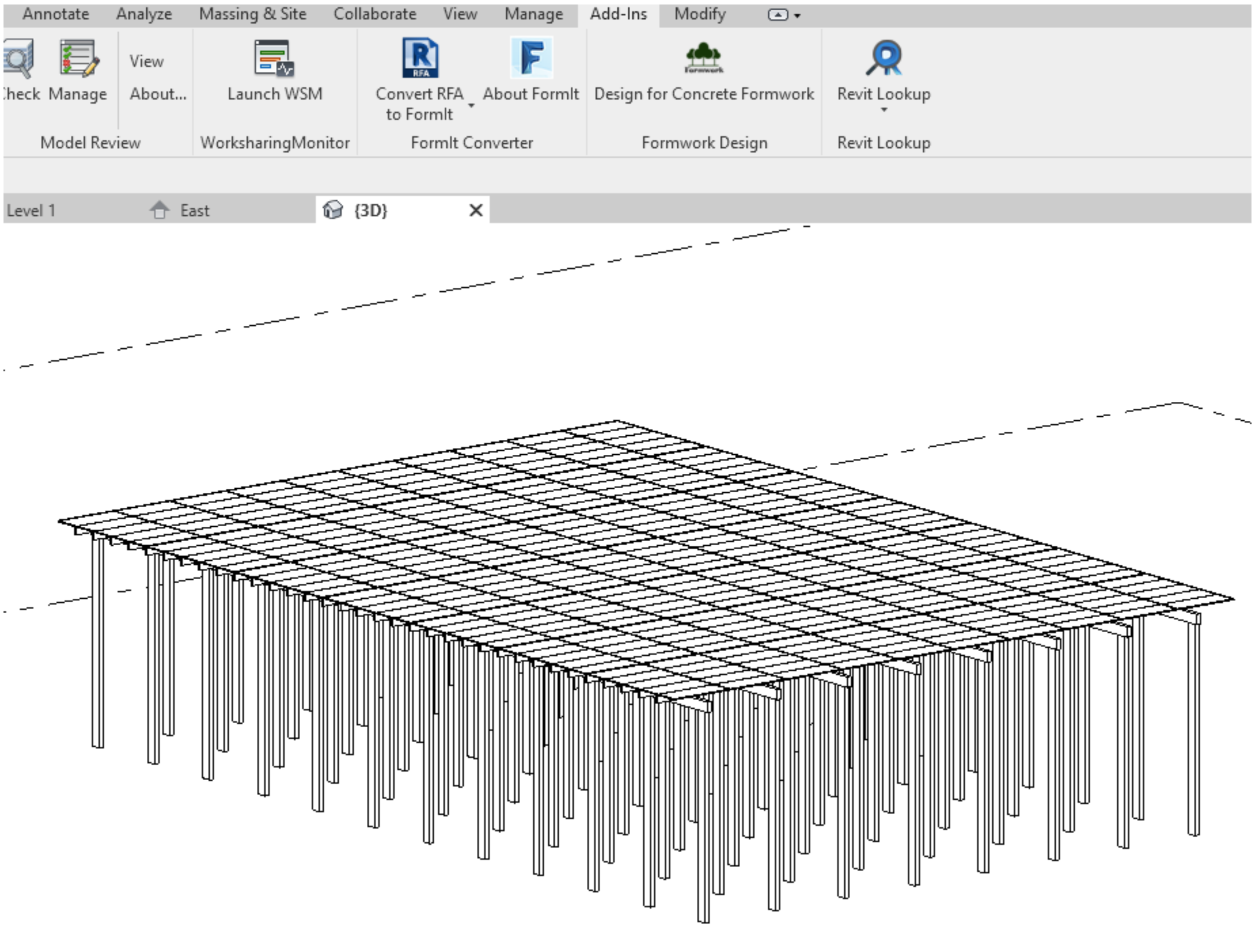
Step 9: In **Tab 7 (Bracing and Planning Suggestions)**, the user can get information about designing slab form bracing, if fall protection measures are required, and if any form component exceeds the recommended maximum load for manual lifting for one person. Such information could be used to at the planning and construction phases, and to improve the safety and health of workers who work with the designed slab forms.



Step 10: In **Tab 8 (Preview and Model)**, a preview of the design slab form is presented. If the user is satisfied with the design decisions, he/she can click the "Model Formwork in Revit" button, and the plug-in will load a pre-modeled integrated slab form family, place a slab form component, and change the parameters based on the design accordingly.



Step 11: The designed slab form system is modeled in Revit (Model elements, such as walls, doors, windows, floors, are made invisible in the Figure shown below).



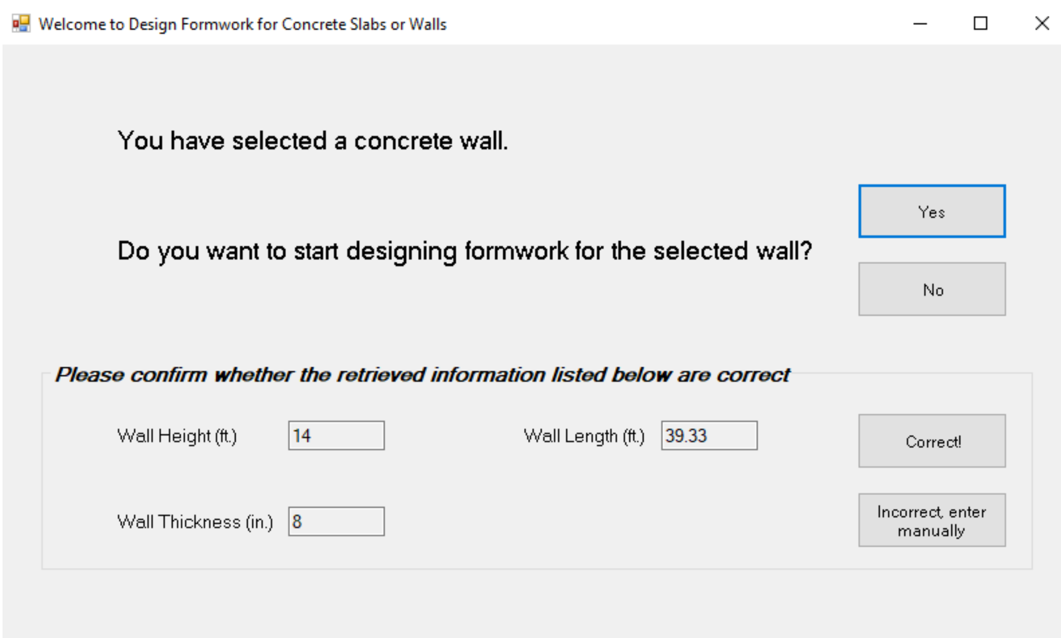
For a Concrete Wall

The **design assumptions** for the selected concrete wall (8 in. thick, 40 ft. wide, and 14 ft. high) are listed as follows.

- Normal-weight (with Type II cement, no pozzolans or set-retarding admixtures) concrete wall;
- Concrete will be placed at a rate of 3ft/hr, internally vibrated;
- Temperature of concrete at placing: 60°F;
- Class I, B-B Plyform sheathing (4 ft. x 8 ft. panels), face grain: horizontal;
- No 2. grade, Douglas Fir-Larch, S4S framing members;
- 2 x 4s for studs and wales;
- 3350 lb (safe working load) ties;
- 2 x 6 in. wedge plates;
- Short-term load duration adjustments will apply to forms;
- Deflection of framing members (sheathing and studs) is limited to the lesser of 1/360 times the span length or 1/16 in.

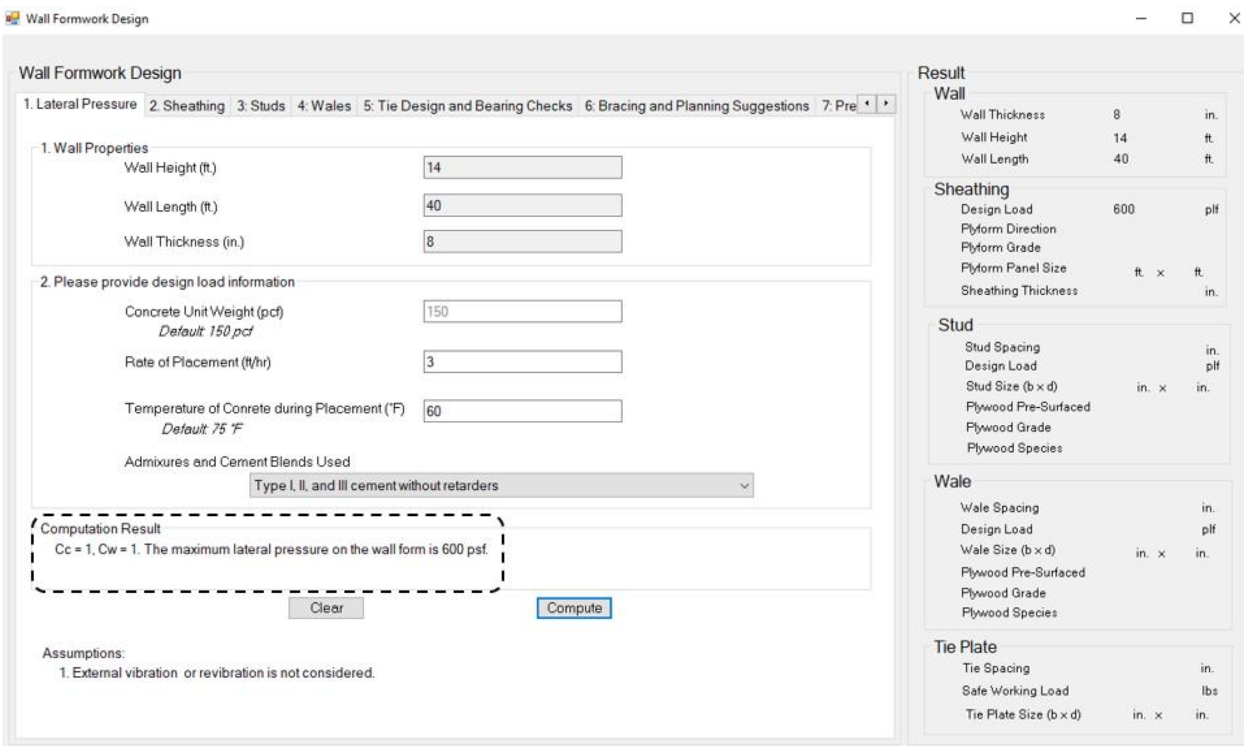
Step 1: Open the plug-in, and the user makes a selection from the Revit model for a concrete wall.

Step 2: The plug-in extracts/computes the parameters of the selected wall (thickness, height, and length). Please note that the user may consider to adjust the retrieved wall length to the full length of the wall (in this case, 40 ft.) by clicking “Incorrect, enter manually”.



Step 3: After the user confirms the retrieved wall information, the main user interface is shown to guide the user through the systematic wall formwork design procedures. After entering/selecting the required and applicable information for calculating lateral pressure for the selected wall (concrete unit weight: 150 pcf, rate of placement: 3 ft/hr, and admixtures and cement blends used: Type I, II, III without retarders) in **Tab 1 (Lateral Pressure)**, the result is shown as follows.

Cc = 1, Cw = 1. The maximum lateral pressure on the wall form is 600 psf.

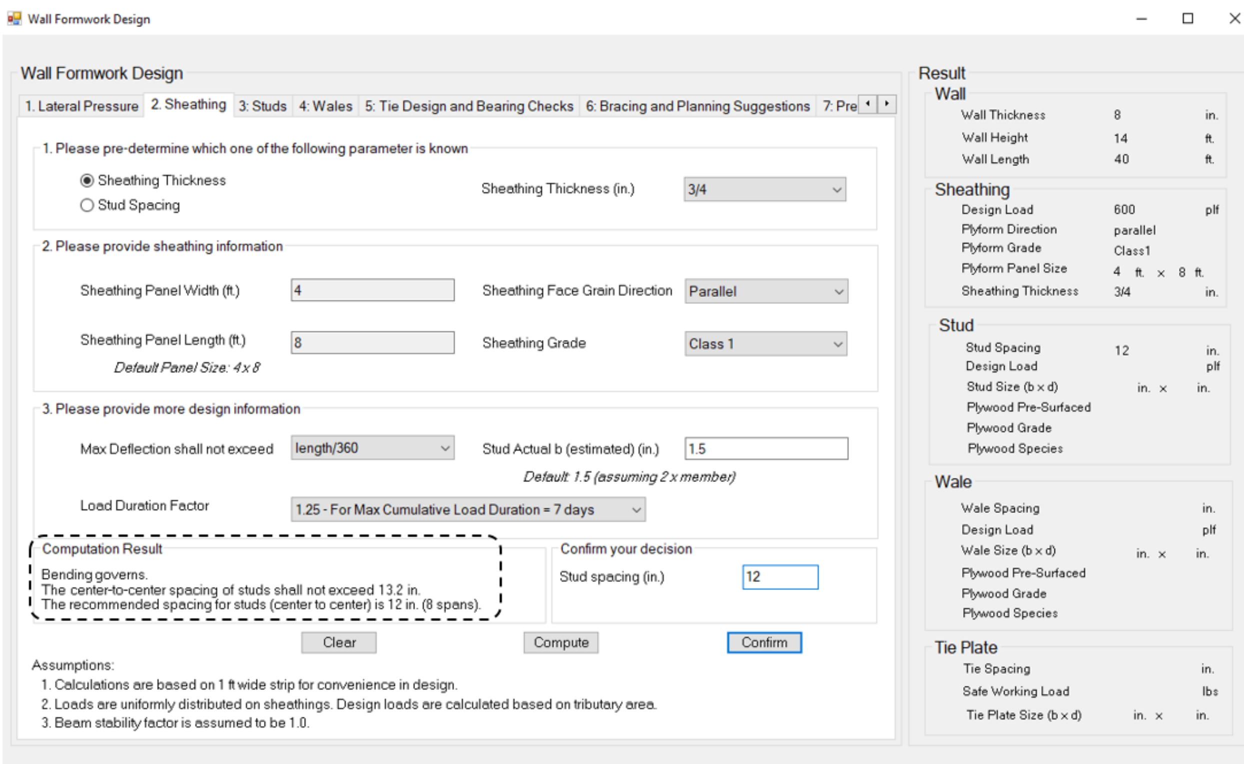


Step 4: In **Tab 2 (Sheathing)**, after entering/selecting the required and applicable information for designing sheathing panels and stud spacing (sheathing thickness: ¾-in, sheathing face grain direction: parallel, sheathing grade: Class I), the computation result is shown as follows:

Bending governs.

The center-to-center spacing of studs shall not exceed 13.2 in.

The recommended spacing for studs (center to center) is 12 in. (8 spans).



Step 5: In **Tab 3 (Studs)**, after entering/selecting the required and applicable information for designing studs and wales spacing (stud size: 2x4, stud pre-surfaced: S4S, grade: No.2, species: Douglas-Fir-Larch), the computation result for wales spacing is shown as follows:

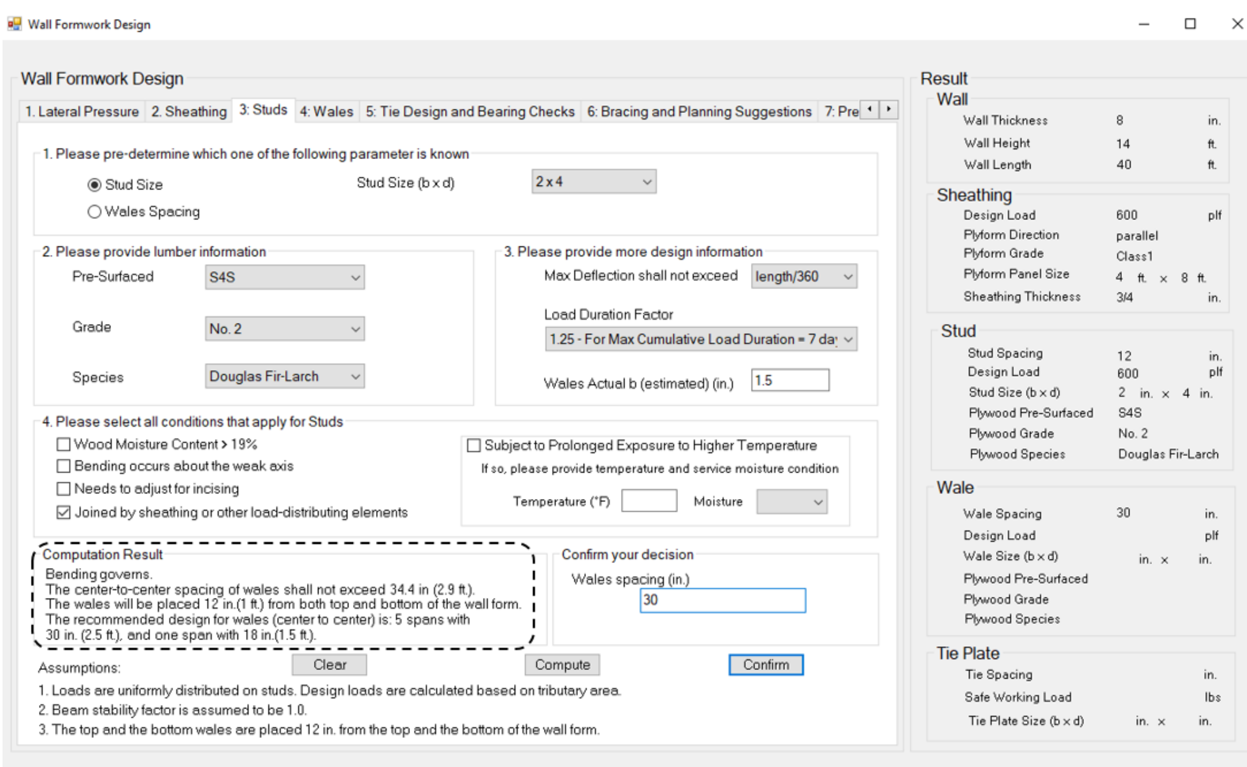
Bending governs.

The center-to-center spacing of wales shall not exceed 34.4 in. (2.9 ft.).

The wales will be placed 12in. (1ft.) from top and bottom of the wall form.

The recommended design for wales (center to center) is: 5 spans with 30 in. (2.5 ft.) and one span with 18 in. (1.5 ft.).

Please note that, different from the original example (Example 7.4) that uses 8 ft. wide and 14 ft. high form panels, the form panels used in this design are 8 ft. wide and 16 ft. high. Each form panel is assembled by four (4 ft. wide and 8 ft. high) sheathing panels. Thus, the spacing of wall form wales are different from the original plan.

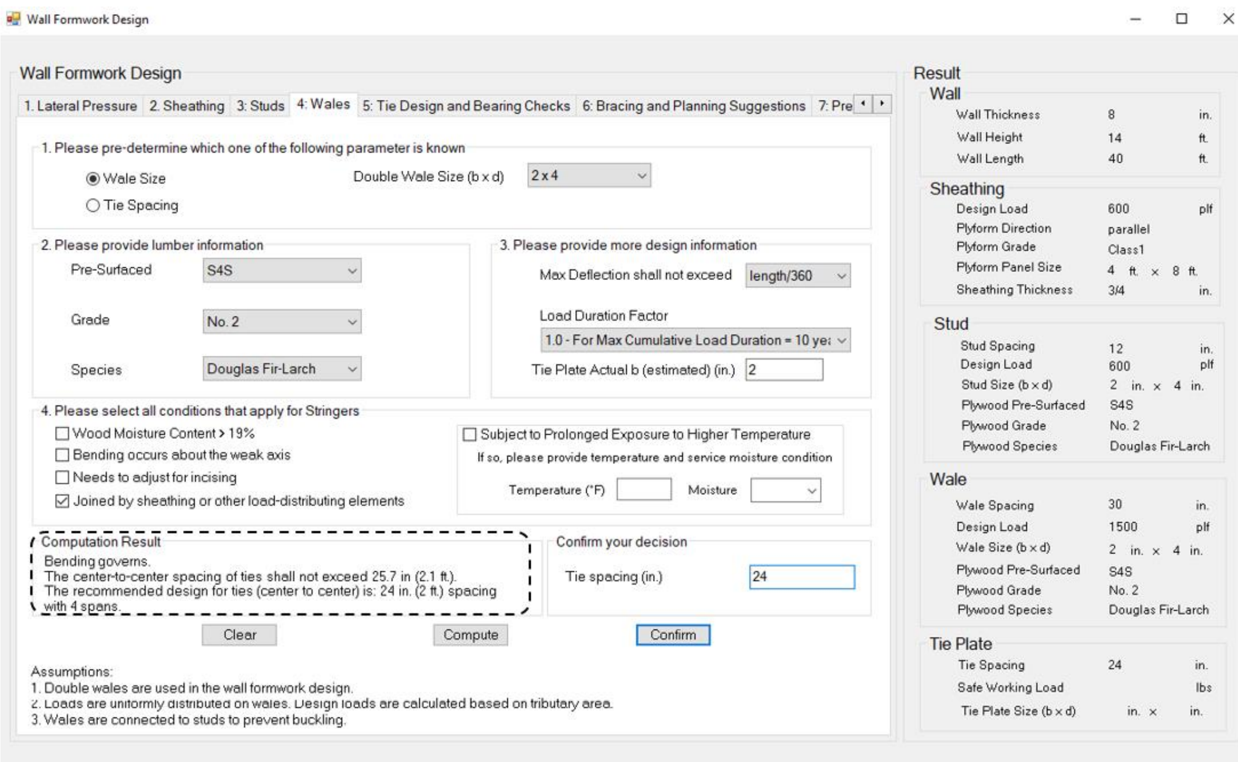


Step 6: In **Tab 4 (Wales)**, after entering/selecting the required and applicable information for designing wales and tie spacing (double wales size: 2x4, wale pre-surfaced: S4S, grade: No 2, species: Douglas-Fir-Larch), the computation result for tie spacing is shown as follows:

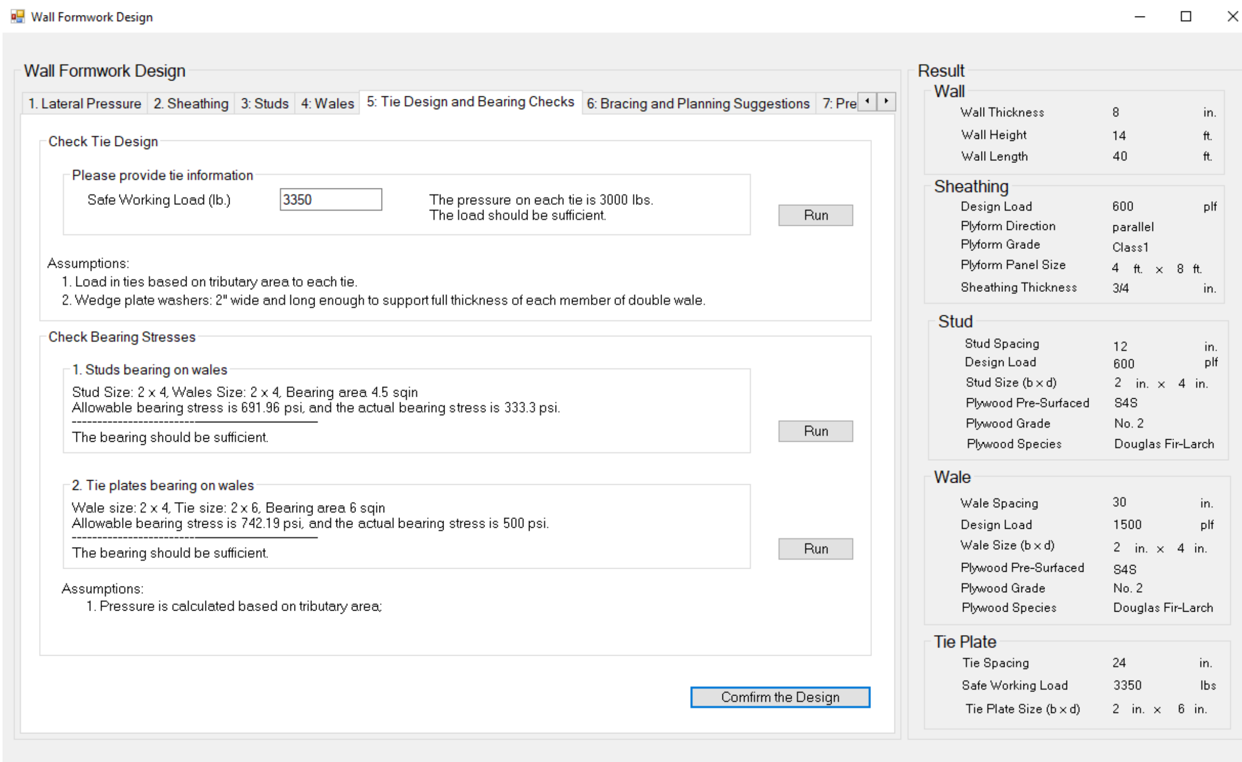
Bending governs.

The center-to-center spacing of ties shall not exceed 25.7 in. (2.1 ft.).

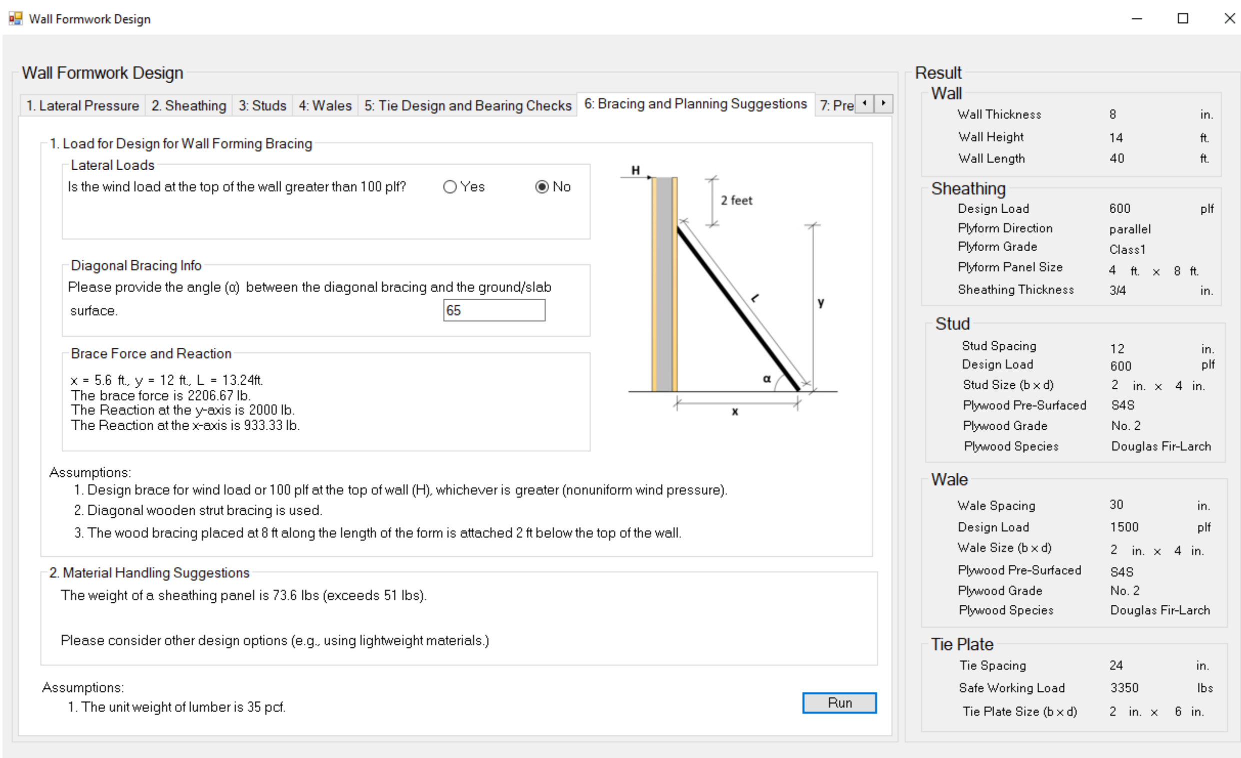
The recommended design for ties (center to center) spacing is: 24 in. (2 ft.) spacing with 4 spans.



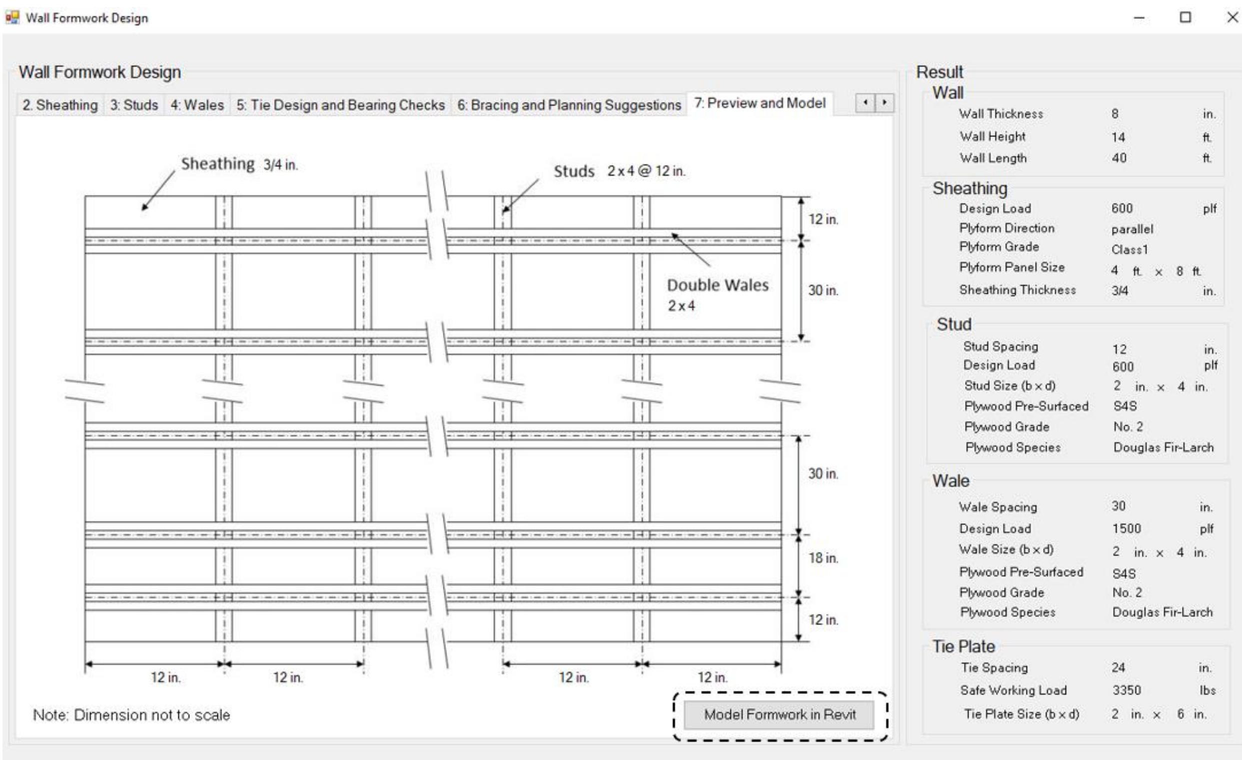
Step 7: In **Tab 5 (Tie Design and Bearing Checks)**, after entering/selecting the required and applicable information for designing ties (safe working load: 3350 lb.), the plug-in can check if the pressure on each tie exceeds the allowable design stress. The user can also check whether bearing stresses (where tie plates bear on wales, and where studs bear on wales) exceed the allowable design stresses.



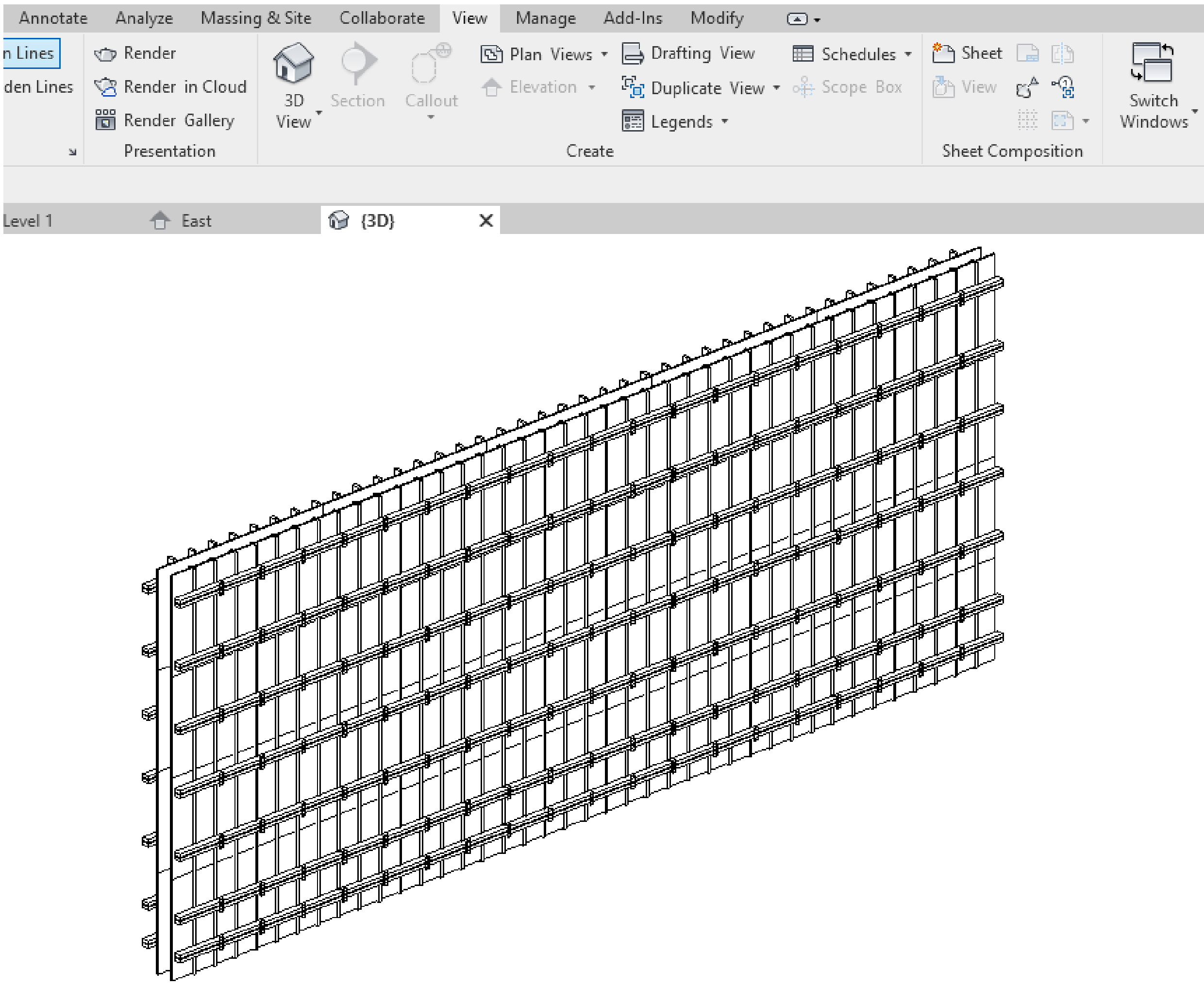
Step 8: In **Tab 6 (Bracing and Planning Suggestions)**, the user can get information about designing wall form bracing, and if any form component exceeds the recommended maximum load for manual lifting for one person. Such information could be used to at the planning and construction phases, and to improve the safety and health of workers who work with the designed wall forms.



Step 9: In **Tab 7 (Preview and Model)**, a preview of the design wall form is presented. If the user is satisfied with the design decisions, he/she can click the "Model Formwork in Revit" button, and the plug-in will load a pre-modeled integrated wall form family, place a wall form component, and change the parameters based on the design accordingly.



Step 10: The designed wall form system is modeled in Revit (Model elements, such as walls, doors, windows, floors, are made invisible in the Figure shown below).



Demonstration Video

A demonstration video that illustrates the examples shown in this document is available at https://youtu.be/_Jo2fg5ghEg.

Latest update on February 17, 2021

Appendix III - Flex Sensor Script

```
#include <SoftwareSerial.h>
#define RX 2
#define TX 3

#include <SPI.h> //for the SD card module
#include <SD.h> // for the SD card
#include <RTClib.h> // for the RTC

// Data logging SD shields and modules: pin 10
const int chipSelect = 10;

// Create a file to store the data
File myFile;

RTC_PCF8523 RTC;

int flexs = A0; // flex sensor is connected with analog pin A0
int data = 0;

// const float VCC = 4.97; // voltage at Arduino 5V line with USB
const float VCC = 4.89;   // voltage at Arduino 5V line with battery
const float R_DIV = 46900.0; // resistor used to create a voltage divider
const float flatResistance = 13600.0; // resistance when the flex sensor is
completely flat
const float bendResistance = 23000.0; // resistance when the flex sensor is at 90
degree


String AP = "xxxx”;      // AP NAME
String PASS = "xxxx"; // AP PASSWORD
String API = "xxxx";   // Write API KEY from the Thingspeak channel
String HOST = "api.thingspeak.com";
String PORT = "80";
int countTrueCommand;
int countTimeCommand;
boolean found = false;
int valSensor = 1;
SoftwareSerial esp8266(RX,TX);

void setup()
{
  Serial.begin(9600);
  pinMode(flexs, INPUT);

  // setup for the RTC
  while(!Serial);
```

```
    if(! RTC.begin()) {
      Serial.println(F("Couldn't find RTC"));
      while (1);
    }
    else {
      RTC.adjust(DateTime(F(__DATE__), F(__TIME__)));
    }
    if(! RTC.isrunning()) {
      Serial.println(F("RTC is NOT running!"));
    }

  // setup for the SD card
  Serial.print(F("Initializing SD card..."));

  if(!SD.begin(chipSelect)) {
    Serial.println(F("initialization failed!"));
    return;
  }
  Serial.println(F("initialization done."));

  //open file
  myFile=SD.open("DATA.csv", FILE_WRITE);

  // if the file is successfully opened, write to it:
  if (myFile) {
    Serial.println(F("File opened ok"));
    // print the headings for the data
    myFile.println("Date,Time,ADCflex,Resistance,Estimated Angle");
  }
  myFile.close();


  esp8266.begin(115200);
  sendCommand("AT",5,"OK");
  sendCommand("AT+CWMODE=1",5,"OK");
  sendCommand("AT+CWJAP=\""+ AP +"\",\""+ PASS +"\"",20,"OK");
}


String getAnalogRead(){
  int ADCflex = analogRead(flexs);
  return String(ADCflex);
}

String getResistance(){
  int Read;
```

```
  Read = getAnalogRead().toInt();
  float Vflex = Read * VCC / 1023.0;
  float Rflex = R_DIV * (VCC / Vflex - 1.0);
  Serial.println("Resistance: " + String(Rflex) + " ohms");
  return String(Rflex);
}

String getFlexAngle (){
  int Rflex;
  Rflex = getResistance().toInt();
  float angle = map(Rflex, flatResistance, bendResistance, 0, 90.0);
  Serial.println("Bend: " + String(angle) + " degrees");
  Serial.println();
  return String(angle);
}


void sendCommand(String command, int maxTime, char readReplay[]) {
  Serial.print(countTrueCommand);
  Serial.print(F(". at command => "));
  Serial.print(command);
  Serial.print(" ");
  while(countTimeCommand < (maxTime*1))
  {
    esp8266.println(command);
    if(esp8266.find(readReplay))
    {
      found = true;
      break;
    }

    countTimeCommand++;
  }

  if(found == true)
  {
    Serial.println("OK");
    countTrueCommand++;
    countTimeCommand = 0;
  }

  if(found == false)
  {
    Serial.println("Fail");
    countTrueCommand = 0;
    countTimeCommand = 0;
```

```
  }
  found = false;
 }


void loggingFlex() {
  float flexdata;
  float flexR;
  float flexAngle;
  flexdata = getAnalogRead().toFloat();
  flexR = getResistance().toFloat();
  flexAngle = getFlexAngle().toFloat();

  if  (isnan(flexdata) {
    Serial.println(F("Failed to read from flex sensor!")); //debugging
    return;
  }

  myFile = SD.open("DATA.csv", FILE_WRITE);
  if (myFile) {
    Serial.println(F("SD card file open with success"));
    myFile.print(flexdata);
    myFile.print(",");
    myFile.print(flexR);
    myFile.print(",");
    myFile.print(flexAngle);
    myFile.println(",");
  }
  myFile.close();
}

void loggingTime() {
  DateTime now = RTC.now();
  myFile = SD.open("DATA.csv", FILE_WRITE);
  if (myFile) {
    myFile.print(now.year(), DEC);
    myFile.print('/');
    myFile.print(now.month(), DEC);
    myFile.print('/');
    myFile.print(now.day(), DEC);
    myFile.print(',');
    myFile.print(now.hour(), DEC);
    myFile.print(':');
    myFile.print(now.minute(), DEC);
    myFile.print(':');
    myFile.print(now.second(), DEC);
```

```
    myFile.print(",");
   }
   Serial.print(now.year(), DEC);
   Serial.print('/');
   Serial.print(now.month(), DEC);
   Serial.print('/');
   Serial.println(now.day(), DEC);
   Serial.print(now.hour(), DEC);
   Serial.print(':');
   Serial.print(now.minute(), DEC);
   Serial.print(':');
   Serial.println(now.second(), DEC);
   myFile.close();
   delay(1000);
}

void loop()
{
   delay(10000);
   loggingTime();
   loggingFlex();

 String getData = "GET /update?api_key="+ API +="&field4="+getFlexAngle();
 sendCommand("AT+CIPMUX=1",5,"OK");
 sendCommand("AT+CIPSTART=0,\"TCP\",\""+ HOST +"\","+
PORT,15,"OK");
 sendCommand("AT+CIPSEND=0," +String(getData.length()+4),4,">");
 esp8266.println(getData);delay(1500);countTrueCommand++;
 sendCommand("AT+CIPCLOSE=0",5,"OK");
 }
```