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Integrating work sequences and temporary structures into safety planning: Automated scaffolding-related safety hazard identification and prevention in BIM

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ABSTRACT

Construction remains as a hazardous industry that can expose construction workers to fatal accidents and illnesses. With recent advances in BIM technology, project information in BIM can be analyzed in the early design and planning stages to address potential safety issues. However, despite the impact on safety and productivity of the entire construction project, temporary structures, such as formwork and scaffolds, are often omitted from drawings or BIM. In practice, it is challenging to consider temporary structures in current manual jobsite safety analysis which is time-consuming and error-prone. As a result, in construction plans, potential safety hazards related to temporary structures are unknowingly created which need to be identified and prevented during the construction phases. Focusing on scaffolds, this research integrates temporary structures into automated safety checking approach using BIM. A safety planning platform was created to simulate and visualize spatial movements of work crews using scaffolding. Computational algorithms in the platform automatically identify safety hazards related to activities working on scaffolding and preventive measures can be prepared before the construction begins. The algorithms were implemented in a commercially available BIM software as a plug-in and validated with a real-world construction project. The results show that the algorithms could identify safety hazards that were not noticed by project managers participating in the case study project. The simulated results are visualized in the developed safety planning platform to potentially facilitate early safety communications.

1. Introduction

1.1. Construction safety planning

Construction remains as a hazardous industry that can potentially expose construction workers to fatal hazards. According to the Occupational Safety and Health Administration (OSHA), the construction industry is responsible for more than 20% of all worker fatalities in the US private sector [1]. Falls from elevation, struck-by objects, electrocutions, and caught-in/between are among leading causes. Also, accidents related to scaffolding account for a large proportion of the causes of the safety hazards. In 2009, there were 54 fatalities from scaffolding and staging [2] with falls from scaffolds forming one of the leading causes of the entire fall fatalities and injuries [3]. Besides falling, improper planning and usages of scaffolds can also cause other types of hazards, such as falling objects from scaffolds, electrocution and spatial conflicts with construction activities.

It is desirable that all such potential safety hazards are identified in the early design and planning stages and preventive actions are taken. However, actual safety planning practices in the construction industry have several drawbacks. Construction safety planning is often conducted separately from the earlier planning efforts [4]. Accordingly, in many construction projects, the roles of safety experts are limited to inspecting construction plans instead of actively participating in the process of establishing and modifying construction plans. Secondly, construction jobsite safety analysis relies heavily on manual efforts of individual safety manager or superintendent to recognize potential safety hazards. Due to complicated and changing nature of construction projects, manual safety checking is usually labor-intensive and error-prone. Furthermore, limited attention has been given to safety during the design phase since designers often do not understand the impact their work has on safety [5]. Currently, the cooperation and communication among project stakeholders related to safety is still limited to project front-end planning stage [6].

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1.2. Impact of temporary structures on safety

Safety planning becomes even more challenging when temporary structures are considered. Temporary structures, such as formwork, scaffolds, and shoring, are used frequently in most construction projects to assist construction activities. The safety, profitability, speed, and quality of the entire project can be impacted by how the temporary structures are planned and used [7]. Despite the importance, existing safety planning practices fail to effectively address safety problems associated with temporary structures. Most of temporary structures do not appear in drawings or BIM, and temporary structures are installed on site often without sufficient planning and analysis [8]. Temporary structure drawings, calculations and execution plans submitted by temporary structure subcontractors are rarely reviewed to analyze the impact on construction safety and productivity [8]. Considering that most construction projects are short of human resources for construction planning, the processes of manually modeling temporary structures in BIM and analyzing all possible safety hazards associated with them can be extremely labor-intensive. Even though there have been successful approaches of using advanced technology to enable effective planning and management of construction safety, few of them presented methods to address safety problems associated with temporary structures.

Despite the wide-spread concerns over scaffold-related safety hazards, scaffolds are insufficiently planned, procured, and managed in construction projects. Safety regulations related to scaffolds are still one of the most frequently violated regulations [9]. According to OSHA, approximated 65% of construction workers are frequently on scaffolding systems. Preventing accidents associated with scaffolds can exclusively protect workers from about 4500 injuries and 50 deaths annually [10]. Proper scaffolding design and construction planning has the potential to save American employers $90 million on lost workdays [10]. These statistics indicate that there is a need for enhanced methods and tools for construction safety planning that take account of temporary structures, especially scaffolds.

Even though there exist regulations and practices, most of them provide general instructions that are directly related to individual elements of temporary structures, such as missing guardrails and improper planking of scaffolds [10,11]. However, occurrences of safety hazards are more strongly tied to underlying causes, such as poor planning, insufficient control, inappropriate operation, etc. [12] Similarly, safety hazards, related to temporary structures, can be triggered by poor safety planning and management [3]. Simple safety and inspection checklist tools widely used today are not effective in addressing safety problems in the early design and planning stages [3].

In order to overcome the drawbacks and meet the needs discussed above, this research attempts to improve construction safety by addressing safety hazards related to temporary structures in the construction planning stage. This paper presents a BIM-based system that incorporates temporary structures and automatically conducts safety hazard identification. Computational algorithms developed in this research automatically identify potential safety hazards associated with temporary structures by analyzing project information contained in BIM and construction schedules. Among various types of temporary structures, this research focuses on scaffolding due to frequent uses in construction and wide-spread concerns over scaffold-related safety hazards.

This paper is organized as follows. Related works section presents a review of existing studies on planning, analyzing, and managing temporary structures using technologies. A point of departure, research objectives, and scope are then derived after the review. Following methodology section presents the BIM-based safety simulation platform and computational algorithms created in this research. In the case study section, the platform and algorithms were implemented and validated in a realistic construction project. The last section concludes the research and discusses contributions, limitations, and potential for future research studies.

2. Related works

This section reviews state-of-the-art computer-assisted approaches to plan temporary structures as part of construction plans and to analyze the impact of temporary structures on safety.

2.1. Computer-assisted temporary structure planning

Temporary structures are used to assist in construction of permanent structures. Therefore, planning of temporary structures is impacted by dynamically changing construction site conditions and characteristics of the construction activities using the temporary structures.

Kim et al. [13] presented a theoretical foundation to analyze construction site conditions to facilitate automated selection of scaffolding types. This research defined a lexicon to analyze geometric and action conditions in digital construction models. In addition, this research proposed a method to analyze building construction site conditions based on the relationship between work faces and base surfaces. For painting activity, work faces are faces of walls to be painted and base surfaces are the top surfaces of slabs where construction workers stand on. However, this research requires work faces and base surfaces to be specified manually by the users. Furthermore, this research does not present computational methods to analyze geometric conditions modeled in various ways in BIM. For example, a work face for a painting activity may contain several wall faces or can be a segment of a wall face.

Kim and Teizer [14] attempted to automate design and planning of scaffolds by addressing the drawbacks of such granularity problems and manual input. This research created a set of algorithms to subdivide and combine individual wall faces to derive work faces and analyze the relationship with slab faces automatically. Even though they automatically analyzed building geometric conditions and generated scaffolding designs based on the OSHA requirements [15], the characteristics of construction activities using the scaffolds were not considered.

There were several successful approaches to generate temporary structure designs. Scia Scaffolding provides scaffolding design functions in the software user-interface to assist in manual creation of detailed scaffolding modeling [16]. It can also automatically conduct code-compliance checking and structural stability analysis after the scaffolding designs are created manually. Smart Scaffolder [17] automatically creates detailed scaffolding designs of specific scaffolding manufacturers. It uses basic building geometry imported from BIM to create scaffolding objects in front of walls and export them to BIM. These commercially available scaffolding design tools often focus mainly on creating and analyzing scaffolding designs for visualization and quantity takeoff. BIM-based scaffolding planning software developed by Kim and Teizer [14] creates scaffolding designs containing essential elements required by the OSHA regulations, but the designs do not have the full details as the benchmark for installation.

2.2. Computer-assisted safety planning

In order to overcome the drawbacks of manual safety planning, several approaches have been proposed both in the industry and academia that take advantage of advanced technology, such as BIM. Zhang et al. [5] proposed an automated safety planning approach using BIM and presented an automated fall protection planning. While this research suggested a desirable direction toward creating safety construction plans, safety hazards related to temporary structures still remain unaddressed. Also, existing computer-based tools and research accomplishments reviewed in Section 2.1 do not present efficient and effective ways to analyze safety issues related to temporary structures. As discussed in the introduction section, temporary structures can make safety planning and management more challenging. This section reviews existing approaches that integrated temporary structures as part of construction plans to identify and prevent safety hazards.

Table 1
Computer-assisted approaches for temporary structure planning.

	Areas of concern	Kim and Fischer [13]	Sulankivi et al. [18]	Akinci et al. [20]	Jongeling et al. [19]	Scia scaffolding [16]	Smart Scaffolder [17]	Kim and Teizer [14]
Planning	(1) Analysis of spatial-temporal conditions	M					I	A
	(2) Temporary structure design generation	I	M		M	M	A	I
	(3) Temporary structure type selection	A						
	(4) Structural stability of temporary structures					A		
Safety analysis	(5) Temporary structure-related safety		M	A	A			

(A: automated, M: manual, I: insufficient automation).

Sulankivi et al. [18] took advantage of realistic visualization of 4D BIM to support manual safety planning. Scaffolding objects were manually inserted into the construction visualization to analyze potential safety problems. Safety features, such as guardrails, were incorporated into the scaffolding objects. Even though this research demonstrated the benefits of using BIM to achieve better site safety, it still requires manual construction site condition analysis and hazard identification. Jongeling et al. [19] attempted to identify potential safety hazards and productivity losses by taking advantage of quantitative information contained in 4D BIM. This research integrated work sequences and temporary structures for concrete construction (formwork and shoring) and measured distances between work crews. While this research proposes an essential step toward automated safety analysis, significant effort is needed to create detailed workflows and temporary structure utilizations before the automated analysis can begin. Furthermore, this approach did not address various safety hazards specific to temporary structures. Similarly, Akinci et al. [20] analyzed workspaces occupied by work crews and temporary structures to identify spatial conflicts, which still requires extensive manual user input before the automated analysis is conducted. Zhang et al. [21] integrated job hazard analysis (JHA) into BIM. Potential safety hazards and preventive actions related to scaffolds for masonry brick construction were automatically shared in BIM. However, this research does not have the capabilities to analyze spatial and temporal conditions presented in BIM to identify unknowingly created safety hazards in a construction plan. Kim and Teizer [14] analyzes spatial-temporal building geometric conditions, creates scaffolding models, and incorporates the models into 4D visualization. But, the scope of this research does not include automated analysis of any potential safety issue related to the scaffolds. This research presents a generic approach that is not customized for specific construction activity, and thus it does not have the function to analyze scaffolding-related safety hazards.

Several commercial available tools have the capability to generate scaffolding design. Scia scaffolding [16] has the capability to create structurally safe scaffolding designs, while it lacks the intelligence to plan scaffolds beyond complying with design requirements. Smart Scaffolder [17] also generates pre-defined types of scaffolding systems automatically around walls. Its advanced interoperability with BIM enables the generated scaffolding models exported into BIM. However, the produced scaffolding models are mainly used for visualization purposes and lack the ability to conduct safety analysis due to missing safety knowledge and disconnection with construction schedule.

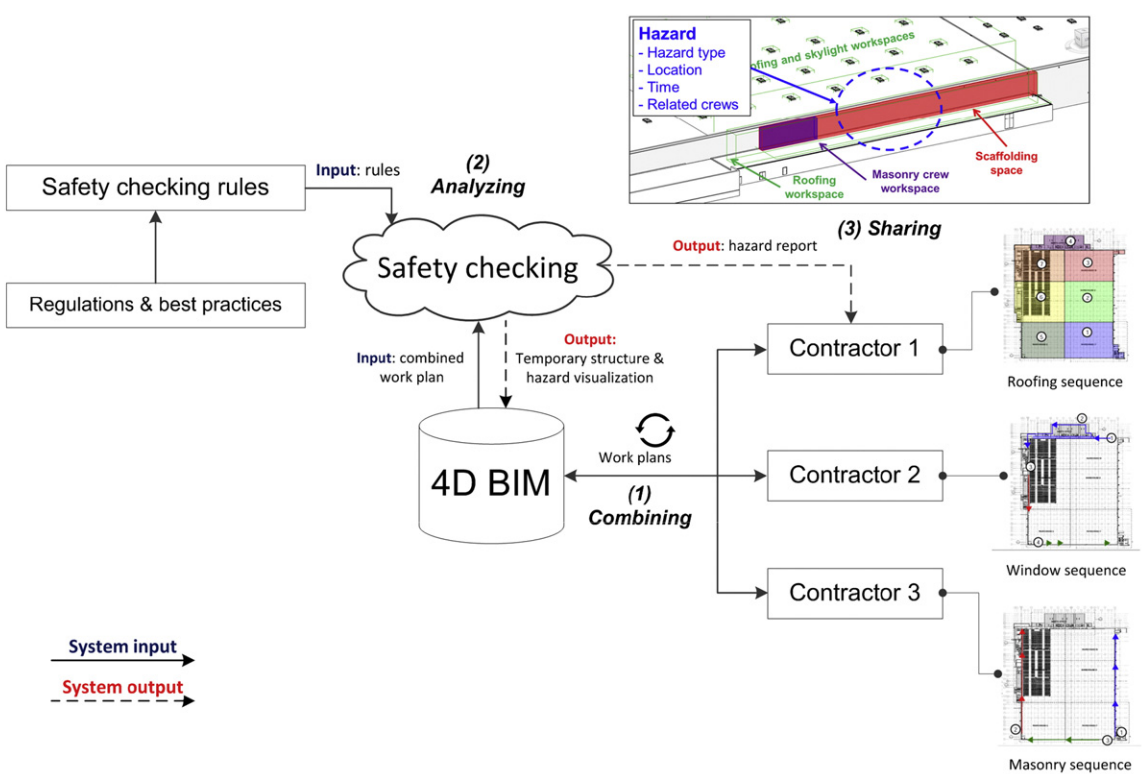


Fig. 1. Framework for automated BIM-safety platform.

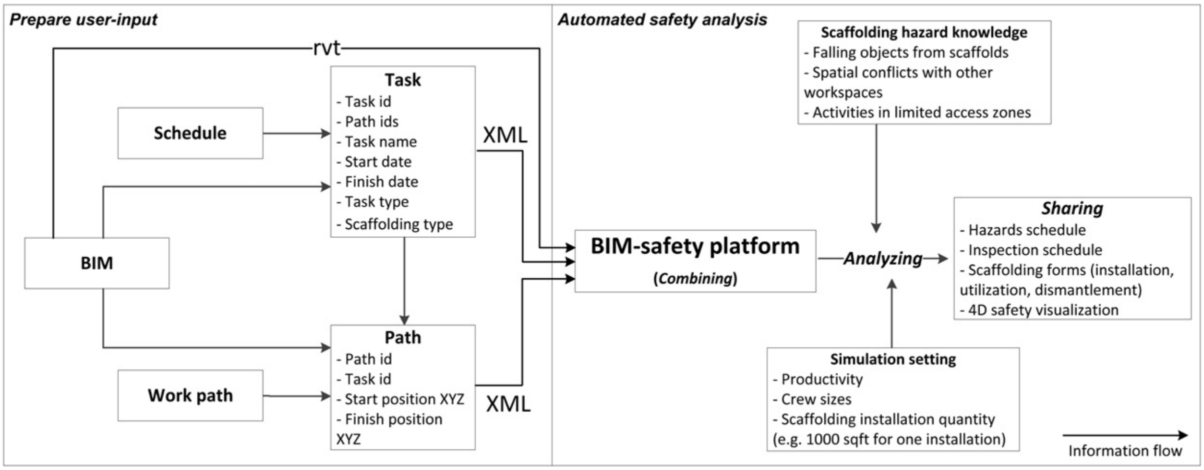


Fig. 2. BIM-safety platform system architecture.

2.3. Point of departure

Model-based technology, such as BIM, is regarded as one of the promising solutions to improve construction management. Many construction projects incorporate temporary structures into the main building models in an attempt to realistically visualize the construction sequences. Table 1 summarizes the state-of-the art approaches reviewed above based on the tasks they attempted to address including: (1) analysis of spatial-temporal conditions, (2) generation of temporary structure designs, (3) temporary structure type selection, (4) structural analysis of temporary structure designs, and (5) safety issues related to temporary structures. In the table, the cross sections between tasks and approaches were marked by "A" if the tasks are properly automated by the approaches. They were marked by "I" if the approaches enable only part of necessary automation. If the tasks are manually conducted in the approaches, they were marked by "M".

The summary shows that the main benefit from the application of the model-based technology is often limited to visualizing the temporary structures in the main building models. The crucial tasks for planning and managing temporary structures have not taken full advantages of the advanced information modeling technology. Temporary structure planning and associated safety analysis still rely on inefficient manual efforts. Based on the review of existing approaches above, remaining technical limitations are summarized as follows:

- *Lack of a method to address safety hazards related to temporary structures*: For realistic safety planning, safety hazards associated with temporary structure utilization need to be analyzed. For example, work crews planned to work adjacent to scaffolds are often exposed to falling object hazards and this situation needs to be identified before the construction begins. While several approaches in the past included temporary structures into the main construction plans, few of them could automatically identify associated safety hazards.
- *The need for intensive manual inputs*: While some of the works presented automatic safety analysis, they required exhaustive manual user inputs. Currently, spatial movements of scaffolds or other temporary structures cannot be simulated in current BIM-based construction planning without extensive manual inputs.
- *Lack of work path planning in 4D BIM*: Spatial movements of crews are usually found in work path plans that are established as part of construction planning. However, current practices often create 4D BIM by integrating 3D building objects with scheduled activities only. The work paths of crews also need to be integrated to account for the spatial movements of crews using temporary structures.

3. Objective and scope

To overcome the technical limitations, this research presents a new approach that integrates work sequences and temporary structures into the automated safety checking system using BIM. There are two tasks to achieve the automated safety analysis.

1. *BIM-safety platform*: Create a platform that incorporates work path plans of crews and their temporary structure utilization to simulate

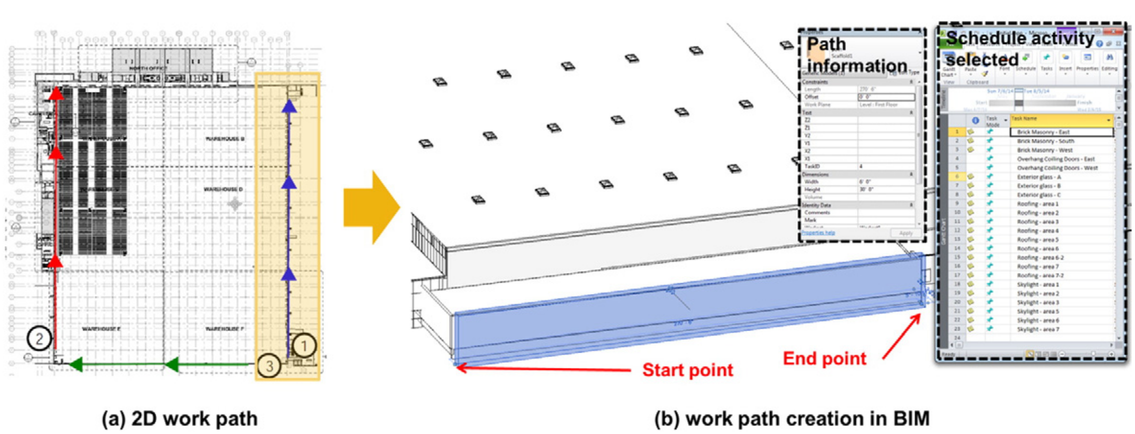


Fig. 3. Manual work path creation for activities using scaffolds (left: realistic masonry path, right: path creation in BIM).

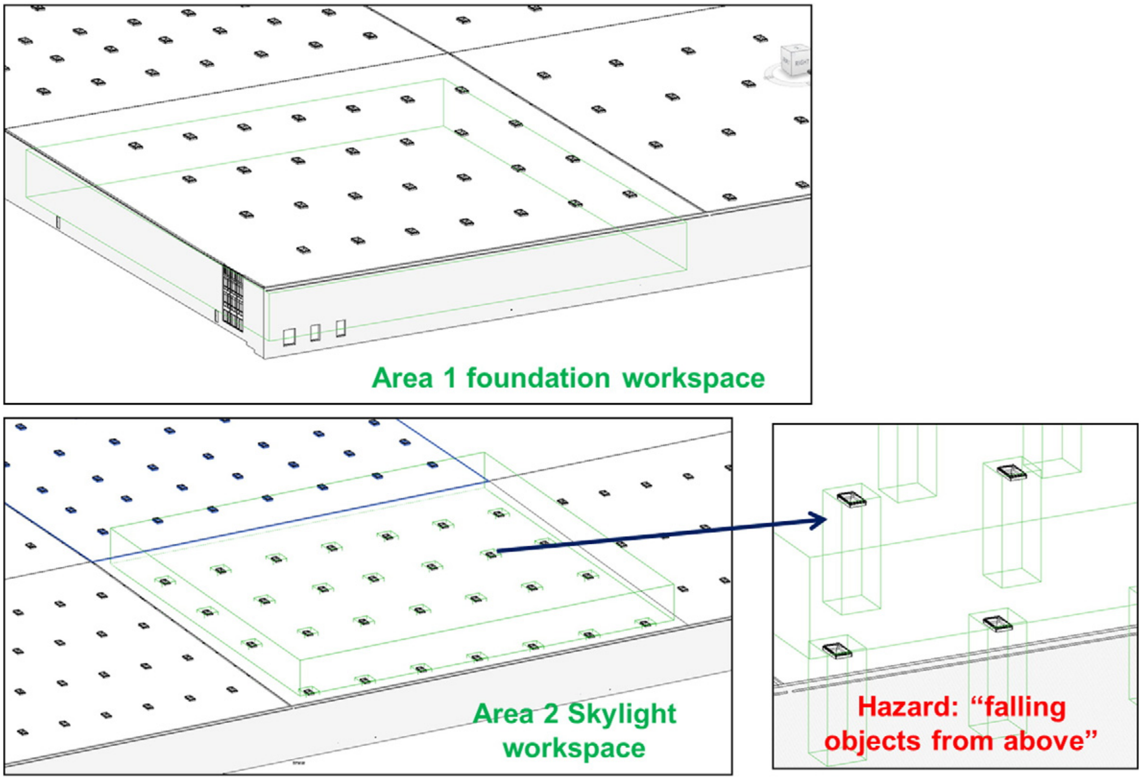


Fig. 4. Workspace generation for activities.

and analyze construction site conditions automatically and realistically.

2. *Safety checking algorithms*: Create computational algorithms in the platform to identify temporary structure-related safety hazards automatically during the construction simulation.

In this research, the scope of temporary structure type is limited to scaffolding. Automated safety checking also focuses on identification of safety hazards related to scaffolding and visualization of the hazards in 3D and 4D. Although this research does not focus on creating detailed designs of scaffolds, it is possible to integrate the outcome of this research into automated scaffolding design generation approaches [14] and other software programs specialized in designing scaffolds. In addition, the end user manually defines worker paths and automatic path generation is not the focus of this research.

4. Development of BIM-based safety analysis automation

The purpose of embedding automated safety analysis capabilities to BIM is to apply the safety regulations, best practices, and safety knowledge during the construction planning stage. This section presents the details of a prototype BIM-based safety analysis automation that includes the framework (Section 4.1.) and technical details and algorithms (Section 4.2.).

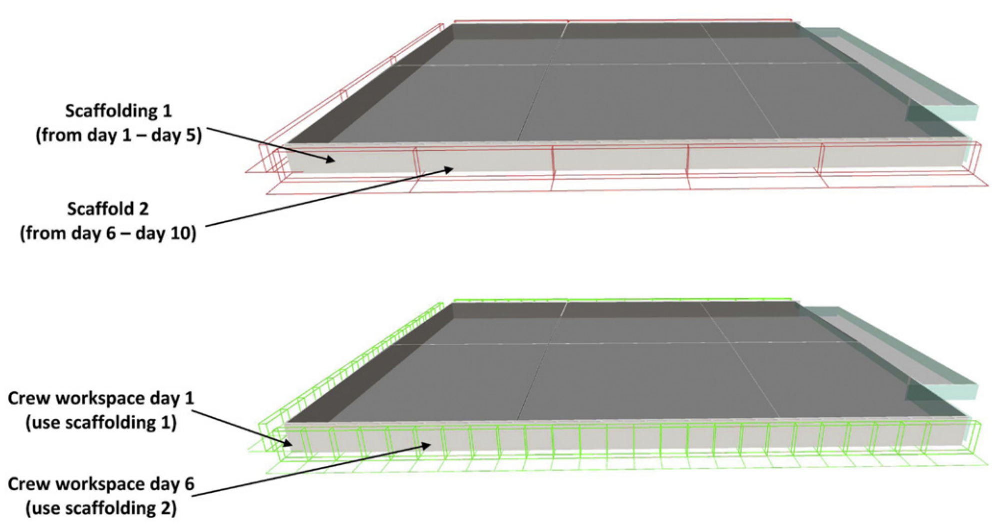


Fig. 5. Automated detail generation based on input work sequence and assumptions.

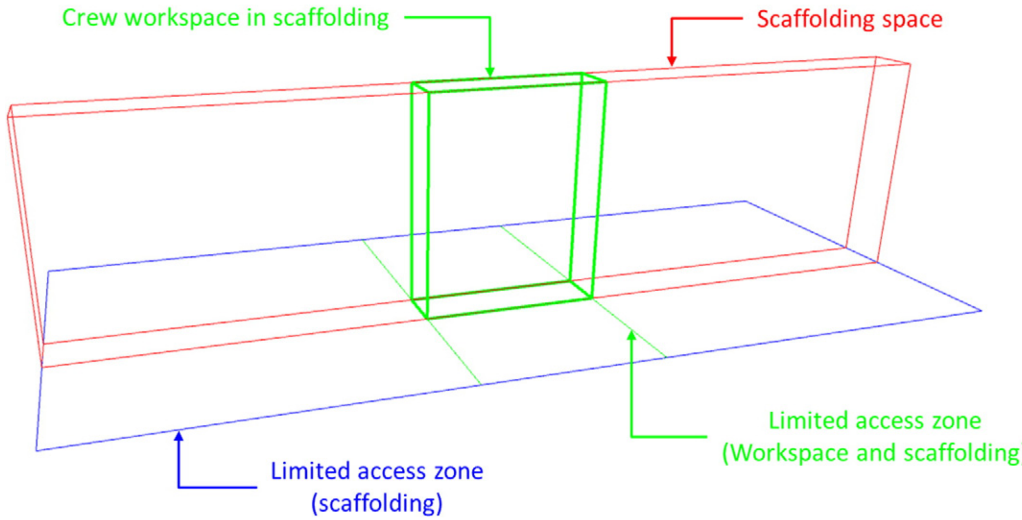


Fig. 6. Scaffolding space, workspace, and limited access zones.

4.1. Framework of BIM-based safety analysis automation

Fig. 1 illustrates a framework of the automated safety hazard analysis.

There are three major functions that are *combining*, *analyzing*, and *sharing*:

(1). *Combining*: Construction site conditions are created by complex interactions between several participants. To properly analyze construction site safety, activities of several subcontractors need to be presented in the construction plan. The combining function integrates the activities of subcontractors as the user-input for the automated safety hazard analysis. In addition to project information in BIM and schedule, work paths and temporary structure utilization of multiple subcontractors are inserted manually in the platform by the users.

(2). *Analyzing*: The analyzing function creates activity details and simulates construction site conditions. To analyze construction site safety realistically, daily work plans of major subcontractors need to be available. However, work plans of such details are rarely available due to the shortage of human resources for construction planning and complexity of projects. Thus, based on user-input, the analyzing function automatically generates details of crew's activities. By doing so, daily construction site conditions are simulated and unsafe conditions are accurately identified. Spatial conflicts between work crews, potential hazards related to scaffolds, such as falling from elevation, and falling objects from scaffolds, are examples of automatically detectable hazards. Upcoming scaffold installation and utilization are automatically identified and populated.

(3). *Sharing*: The sharing function disseminates the results of activity detail generation and safety analysis to construction stakeholders (such as superintendents, field workers, safety inspectors, etc.). This allows potential safety issues identified in the previous step to be communicated and proactively resolved before the construction begins.

4.2. Technical details of BIM-safety platform

The technical details of the prototype are presented in this section. Fig. 2 illustrates the prototype system architecture. Autodesk Revit (BIM), Microsoft Project (schedule), and their Application Programming Interfaces (APIs) were used for the prototype development.

4.2.1. User-input preparation and combining

The first step is to prepare user-input needed for the simulation. As shown in the system architecture, the BIM-safety platform utilizes BIM, schedule, and work paths as the essential inputs. While BIM and construction schedule are basic resources used to create a 4D BIM simulation, this research incorporates paths of work crews in order to account for the movements of crews using scaffolds. In practice, work path plans are established commonly for major construction activities by drawing arrows on 2D drawings to represent the crews' work directions as show in Fig. 3 (a). In this prototype, the users are prompted to insert the paths in 3D environment of BIM. Fig. 3 (a) shows the masonry wall paths in a real construction plan. Fig. 3 (b) shows a work path

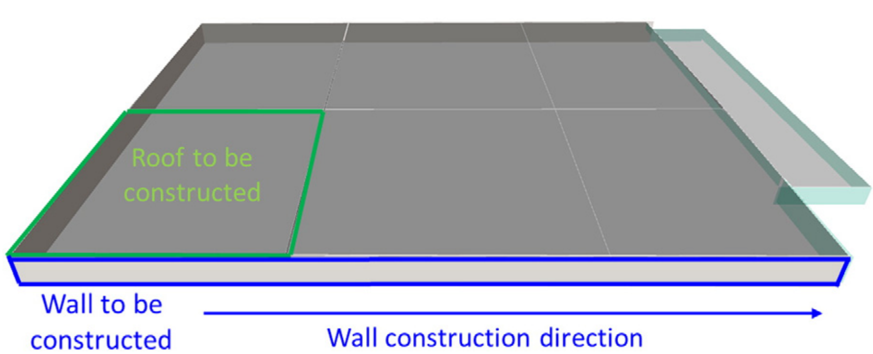


Fig. 7. 4D BIM with on-going construction tasks highlighted.

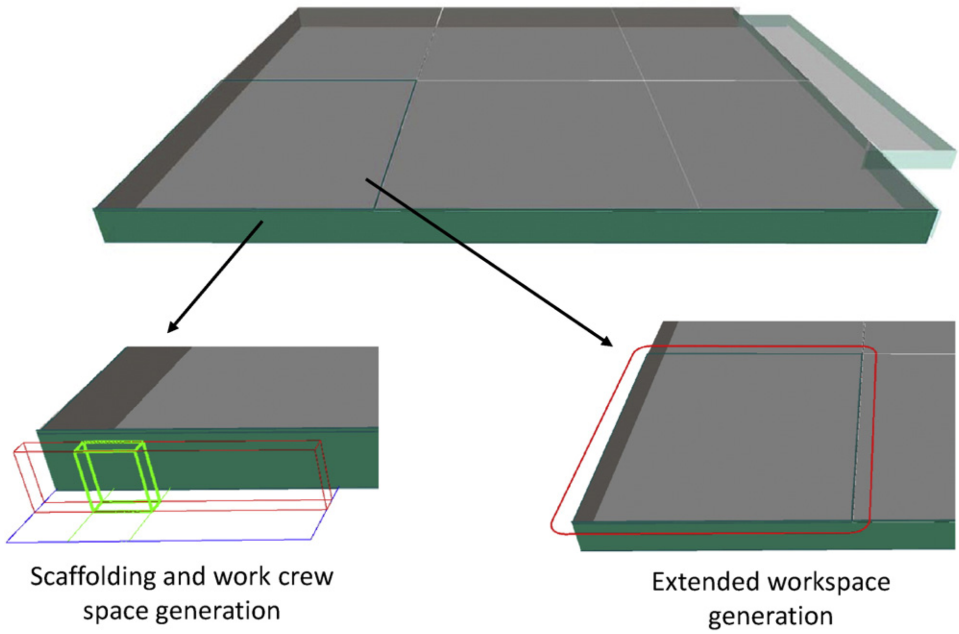


Fig. 8. Workspace generation for the building model.

generated in the prototype system. A path instance created in BIM contains a 3D start point, an end point, and a related task (e.g. painting). To define scaffolding requirements, a task instance contains information on what type and height of scaffold is needed (See task and path in Fig. 2).

After preparing the user-input, our custom BIM plug-in generates and combines XML files for tasks and paths. In addition to building model information, the task and path XML files are essential inputs for the automated safety simulation.

4.2.2. Analyzing and sharing

The prototype system uses workspaces as the basic spatial elements for safety analysis. For activities that are not associated with any path plan, the prototype system created workspaces based on the zoning plans. For activities linked to work paths, the prototype system generates daily crew workspaces and scaffolding spaces along the paths. Then, the prototype system uses the workspaces and scaffolding spaces for safety analysis. Further details are presented below.

4.2.2.1. Workspace generation. Creating workspaces as part of construction planning has been used by several research studies in the past. Methods have been developed to create workspaces based on building objects [20] or characteristics of tasks [22]. In our approach, the prototype system automatically creates workspaces based on the zoning plans that commonly exist as essential part of construction strategies. Since construction zones provide boundaries of work packages and sequences among them, the prototype BIM-safety platform uses the geometry of zones to create workspaces occupied by work crews. Fig. 4 illustrates workspaces generated for different zones. The green box in Fig. 4 (a) shows a workspace for foundation construction and the green box in Fig. 4 (b) presents a workspace for skylight installation. In addition to the zone boundaries, the prototype system created the workspace below each skylight to account for the potential "falling objects from above" hazard (see Fig. 4 (c)).

4.2.2.2. Activity detail generation. Work paths of major activities are generally planned by the superintendents as part of the construction strategy. Conventional path plans in 2D drawings do not contain enough details about the day-to-day activities of construction crews. For example, the path in Fig. 3 (a) presents the planned direction of the masonry crew along the wall. When the amount of brick masonry installation is large, such work packages are often constructed in multiple days depending on the productivity and number of work crews. Unlike workspace generation using zoning plans, activity details thus need to be generated before creating workspaces for activities that contain paths. Fig. 5 shows activity details related to a brick masonry wall construction automatically generated by our prototype system. The prototype system automatically subdivides the entire space in front of the masonry walls based on estimated crew productivity and the size of

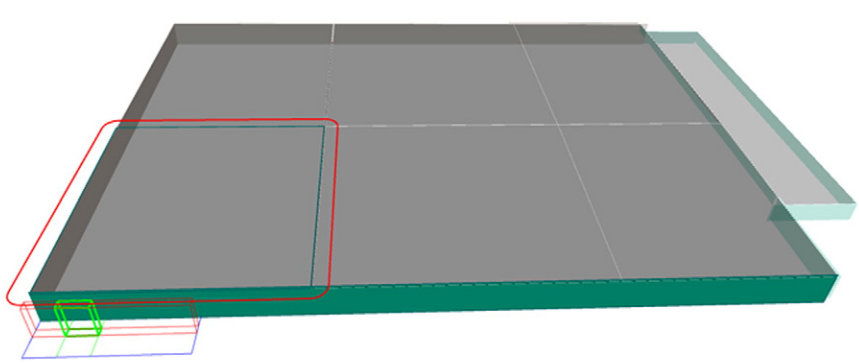


Fig. 9. 4D BIM with spatial information integrated.

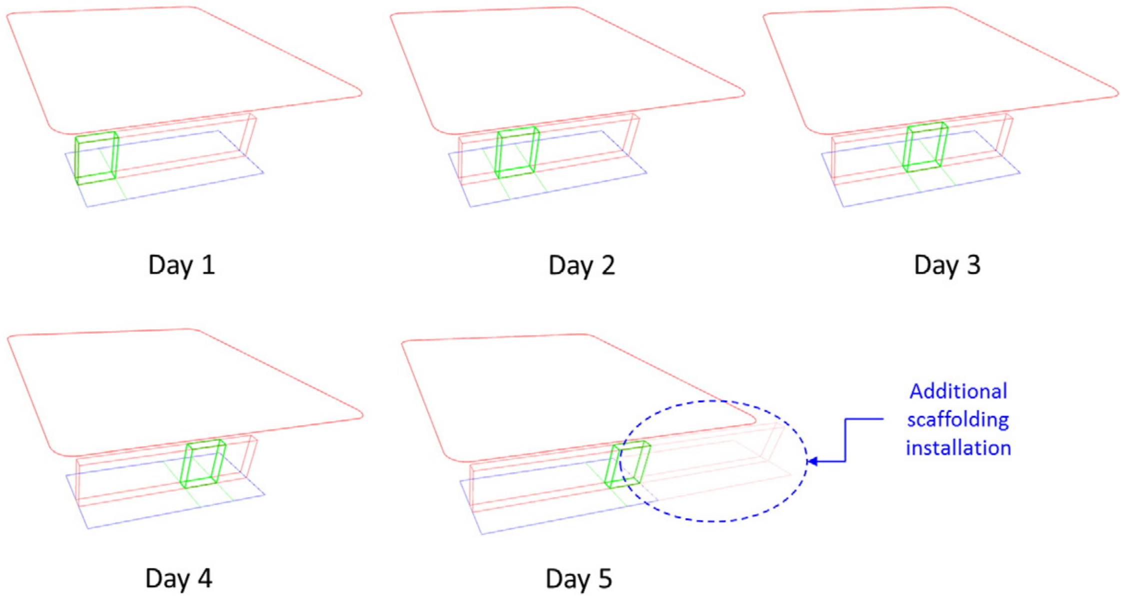


Fig. 10. Daily workspace movement and scaffolding installation.

scaffolding installation. The system also determines the movement directions of the workspaces and scaffolding spaces during the simulation using the work paths specified during the user-input preparation. Fig. 6 illustrates a scaffolding object in BIM that contains crew workspaces, scaffolding spaces, and limited access zones on both sides of scaffolding. A workspace is a space occupied by a crew on a certain day and this space is in the scaffolding space when the crew is using a scaffold. Limited access zones are areas that are restricted from utilization by other activities except the crews using the scaffold. Therefore, these limited access zones were used in this research to identify potential safety hazards.

Figs. 7, 8, and 9 illustrate an example of daily activity detail generation. In Fig. 7, a building model is shown and a roof and a wall to be constructed are highlighted. The wall is planned to be constructed following the work direction presented by the arrow. As a result of applying the space generation algorithm, the prototype system generated scaffolding and work crew spaces for the wall construction (Fig. 8). Also, the system generated a workspace for a roof construction by extending the boundary of the roof (Fig. 8). Fig. 9 illustrates the spatial elements integrated into the 4D BIM. In this way, the prototype system automatically generates daily details of crew activities as well as scaffolding utilization without excessive manual efforts. Fig. 10 shows workspaces and scaffolding spaces, for each day, automatically generated by the prototype system.

4.2.2.3. Safety simulation and hazard identification. After details including workspaces, scaffolds, and safety components (e.g. limited access zones) are created for each activity, the prototype system simulates construction site conditions of each day. The hazard identification utilizes the scaffolding safety knowledge that explains what types of safety hazards can potentially occur in certain situations. This research obtained the knowledge base from safety regulations and interviews with industry professionals.

As discussed in the introduction section, scaffolding can cause many types of safety hazards including falls, falling objects from scaffolding, electrocution, spatial conflicts, and structural failure of scaffolding. Some of the hazards can be prevented by properly designing and inspecting scaffolds according to safety regulations. However, causes of struck-by objects hazards, such as spatial conflicts and falling objects, can be prevented through better planning rather than focusing on scaffolding designs and inspections. Between 1992 and 2010, being struck by an object was the third leading cause of fatalities responsible for more than 2000 deaths and the first leading cause of non-fatal injuries [23]. Even though statistics of struck-by object hazards related to scaffolding cannot be found, a certain proportion of the hazards can be prevented by properly planning scaffolds. In this research, we conducted interviews with two general contractors, three scaffolding subcontractors, and two masonry subcontractors to define a list of conditions related to scaffolding that can cause struck-by safety hazards. Industry experts have been selected based on years of experience and familiarity to scaffolding. We interviewed nine experts with an average of 18 years and a minimum experience of eight years. The experts were asked to specify potential safety hazards related to scaffolding with examples illustrating the spatial-temporal conditions. Then, the results were

Table 2
Industry expert participation in prototype development.

Companies	Participating experts	Roles			
		Define safety rules	Review simulation	Review safety analysis	Validation w/ case study
General contractor 1	2 construction managers (VDC), 1 safety manager	√	√	√	√
General contractor 2	1 construction manager	√	√	√	
Scaffolding subcontractor 1	1 scaffolding designer	√			
Scaffolding subcontractor 2	1 scaffolding designer	√			
Scaffolding subcontractor 3	1 scaffolding designer	√			
Masonry subcontractor 1	1 engineer	√		√	
Masonry subcontractor 2	1 engineer	√			

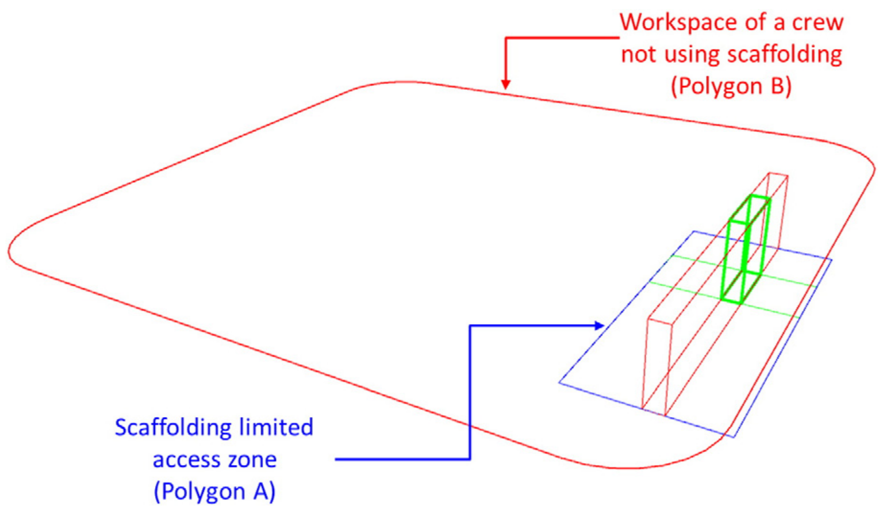


Fig. 11. A conflict between a workspace and a scaffolding space.

organized by the authors into detection rules. As shown below, three types of conditions were identified and converted into computer-readable codes. Based on the interviews with engineers with diverse backgrounds, it was found that struck-by safety hazards related to scaffolding can be detected based on the spatial relationships between workspaces and scaffolding spaces. The three conditions derived from the interviews are believed to represent most of the struck-by hazards related to scaffolding. After the conversion of the conditions into computer-readable codes, the accuracy of the algorithms was assessed by reviewing the checking results with two general contractors and one subcontractor participating in the interviews. In this development stage, the algorithms were refined until all potential hazards could be detected. Table 2 shows the participations of industry experts in the development and validation of the prototype. Even though scaffolding design generation is not in the scope of this research, incorporating detailed scaffolding designs and utilizing them for benchmark for installation and inspection would make the system to address most of safety hazards related to scaffolding.

1. *Workspace-scaffolding space conflict* (Fig. 11)
   Condition: If a scaffold is installed in the workspace of a crew not using the scaffolding.
   Hazard: There is a potential of safety hazards caused by spatial conflicts between the spaces.
   Detection criteria: (1) Polygon A and Polygon B intersect in XY plane. (2) Height difference between Polygon A and Polygon B is within a predefined tolerance (e.g. 2 m).

2. *Falling objects from scaffolds* (Fig. 12)
   Condition: If the workspace of a crew is below a limited access zone of a scaffolding.
   Hazard: The crew is under the risk of falling objects from scaffolding installation, utilization, and dismantlement.
   Detection criteria: (1) Polygon A and Polygon B intersect in XY plane. (2) The height of Polygon A is greater than the height of Polygon B for more than a predefined distance (e.g. 2 m).

3. *Falling objects to scaffolds* (Fig. 13)
   Condition: If the workspace of a crew horizontally intersects with a limited access zone of a scaffold and the workspace is higher than the height of the scaffold.
   Hazard: The crew using the scaffold is under the risk of falling objects to the scaffold.
   Detection criteria: (1) Polygon A and Polygon B intersect in XY plane. (2) The height of Polygon B is greater than the height of Polygon A for more than a predefined distance (e.g. 2 m).

Then, the hazard identification algorithms automatically detect the conditions along the safety simulation. Fig. 14 shows the graphical user-interface (GUI) of the 4D safety simulation, which includes the following main components. GUI (a) and (b) are related to user-input preparation and other parts of the GUI (c, d, e, f, and g) are used to share the result of the safety analysis.

(a) XML files: XML files for tasks and paths created during user-input preparation step are imported to the simulation.
(b) Assumptions: Assumptions about work crews and scaffolds are defined here and used as simulation setting.
(c) 4D calendar: 4D calendar allows the users to select a date to

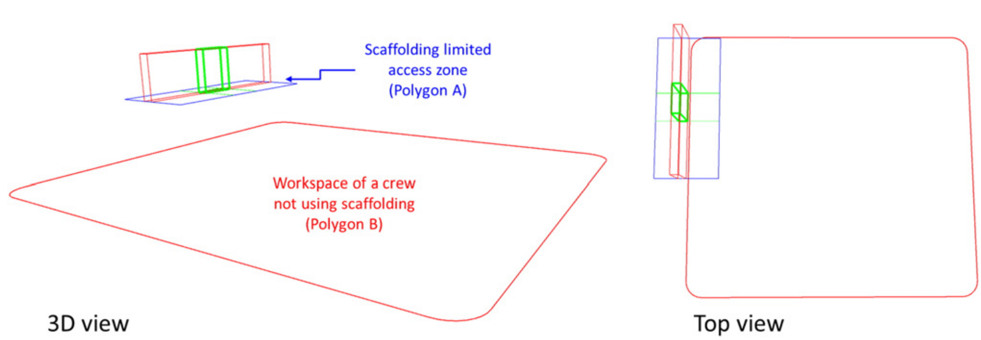


Fig. 12. Falling objects from scaffolding.

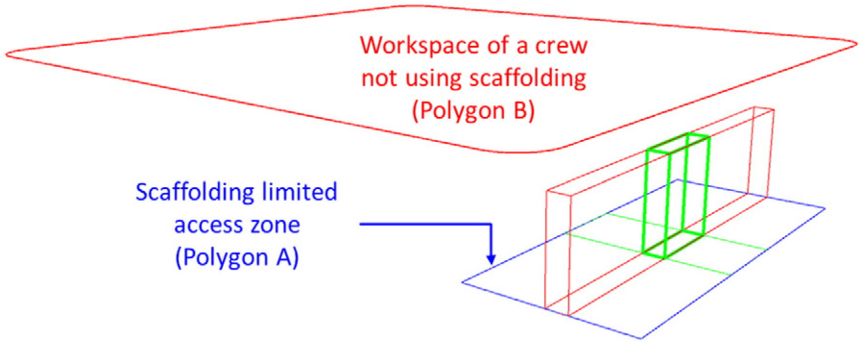


Fig. 13. Falling objects to scaffolding.

review the result of hazard identification.

(d) Active tasks: This shows a list of ongoing activities on the day chosen in 4D calendar.

(e) Safety hazards: Potential safety hazards related to the ongoing tasks identified by the algorithms are listed here.

(f) Inspections: In addition to safety hazards, required scaffolding inspections are listed.

(g) Prevention methods: In addition to safety hazards, commonly used forms and Job Hazard Analysis (JHA) manual can potentially be incorporated into the system as in Zhang et al. [21].

4.2.2.4. Scaffolding-related report creation. In addition to the simulation results directly viewed from the graphical user interface (Fig. 14), various documents and reports can potentially be integrated to assist in

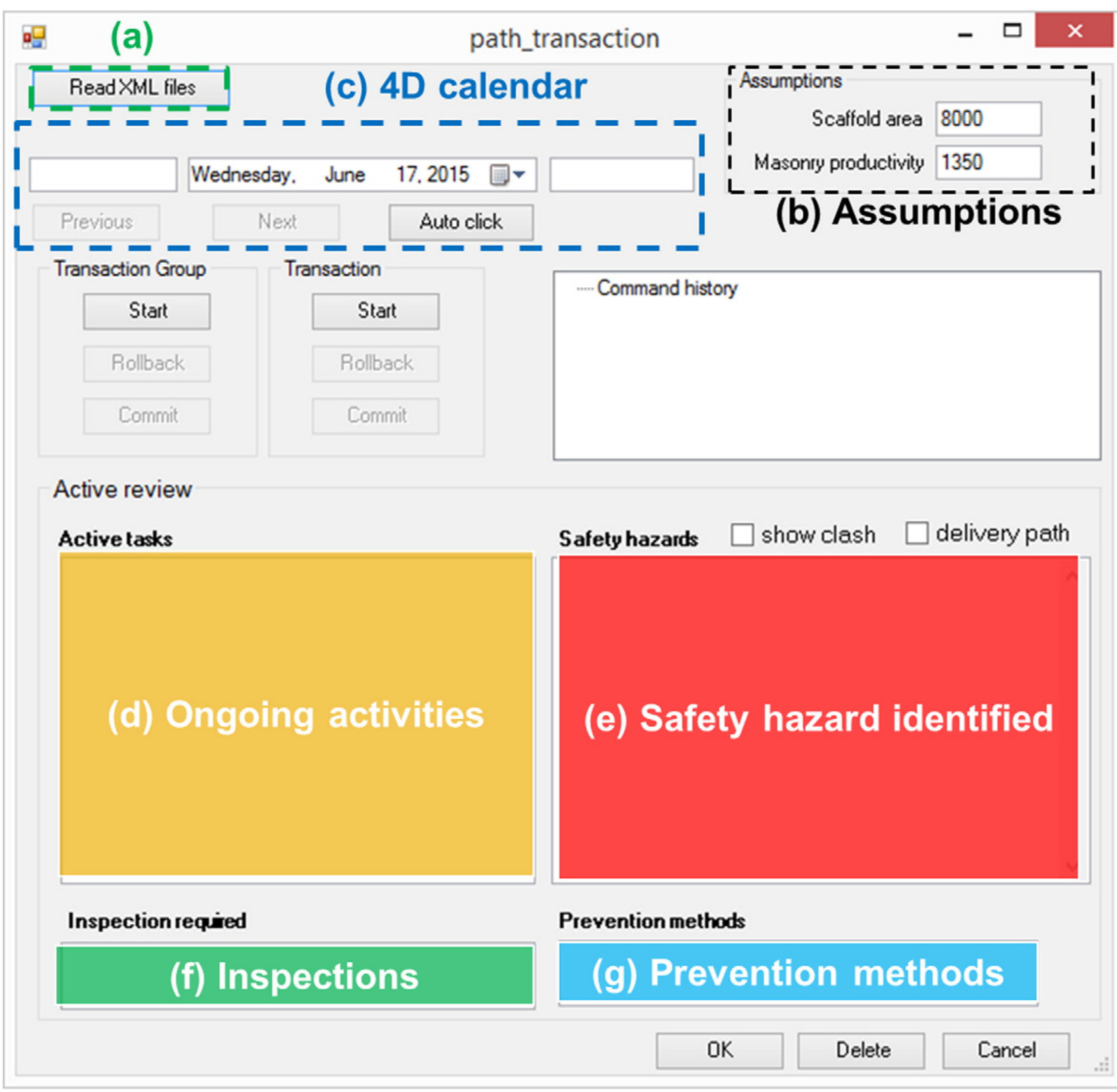


Fig. 14. Safety simulation graphical user interface.

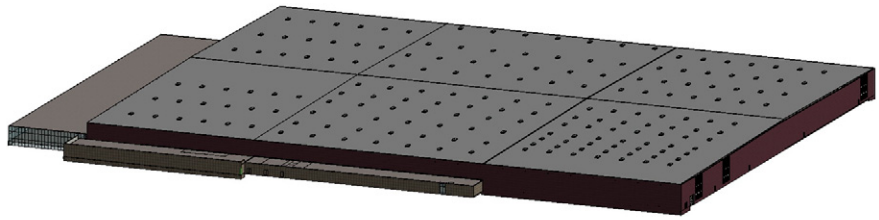


Fig. 15. BIM for a real building construction project.

communication between stakeholders. As identified by CII [24], there are several paper-based tools widely used for planning and managing scaffolds. Most of the tools, such as estimating worksheet, scaffolding utilization report, and installation/dismantlement request forms, can potentially be integrated into the BIM-safety platform. Integration of such reports can eliminate the needs for manual and repeated data input.

5. Case study for validation

This section presents a validation of the prototype system through a case study. Using a real-world construction project, a case study has been designed based on a close collaboration with the construction and safety managers onvolved in the construction project. They participated in the entire process of (1) customizing the algorithms for the case study, (2) creating user input, (3) evaluating the daily construction site simulation, and (4) checking the results of safety analysis. Once daily safety hazards were identified by the developed prototype, a panel of two construction managers and one safety manager of the project reviewed the result and compared it with the potential safety hazards that were actually perceived by the managers in the project. Details about the case study development and evaluation are presented below.

We developed the BIM-safety platform using commercially available software tools and their APIs (Autodesk Revit and Microsoft Project) and applied it in a real construction project. The construction project shown in Fig. 15 is a 600,000 square feet (or 56,000 m^2) large single-story commercial building that needed scaffolds to assist in brick masonry exterior wall construction. The total length of the brick masonry construction is about 5000 feet (1500 m) and the average wall height is 40 feet (12 m). The general contractor of the project created a construction schedule, zoning and path plans for subcontractors including foundation, steel structures, masonry wall construction, roofing and skylight, exterior wall window installation, etc. For this case study, the general contractor of the project provided the construction planning information (BIM, construction schedule, and path plans for major activities). Fig. 16 illustrates zoning and work path plans for the major activities. As discussed in the previous section, workspaces were created for activities with zoning plans and daily details were created for activities with work path plans.

Firstly, a conventional 4D BIM was created in the platform by linking activities in the construction schedule and building objects in BIM. Zoning and work path plans were incorporated. Then, the following estimated assumptions for masonry brick installation were made:

- Daily output: two installation crews (1350 square feet per day);
- Scaffolding: supported scaffolds used, install 8000 square feet of scaffold at a time, a scaffolding installation take one day before the scaffold is required.

Based on the project planning information and assumptions provided from the contractors, the BIM-safety platform simulated the construction site conditions. Safety hazards identified during the simulation were listed in the "Safety hazard identified" section in the user interface (Fig. 14). Fig. 17 shows visualizations of changing construction site conditions using workspaces, scaffolding spaces, and limited access zones during the simulation. The rectangular boxes represent workspaces and objects in front of the exterior walls represent scaffolding objects. Each scaffolding object contains daily workspace in the scaffolding space and limited access zones. For each day, safety hazards were identified and the list was shown in the user interface (Fig. 18). A scaffolding installation schedule was also visualized which can assist in timely scaffolding material delivery and installation (Fig. 19).

The automated safety checking detected potential safety issues. Even though the safety experts conducted daily safety analysis during construction, they did not document the results of their manual safety analysis. Therefore, a safety manager who actively conducted construction

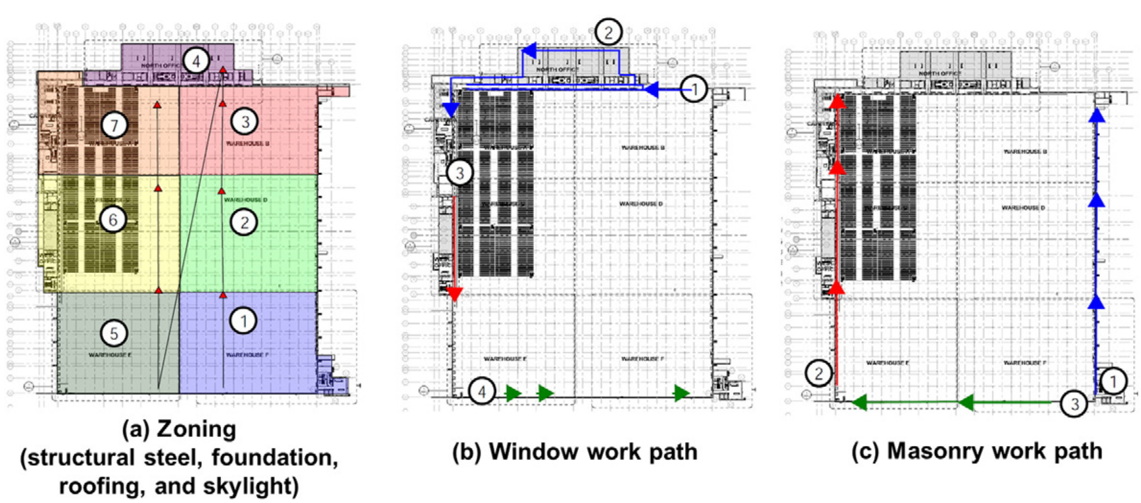


Fig. 16. Zoning and work path plans.

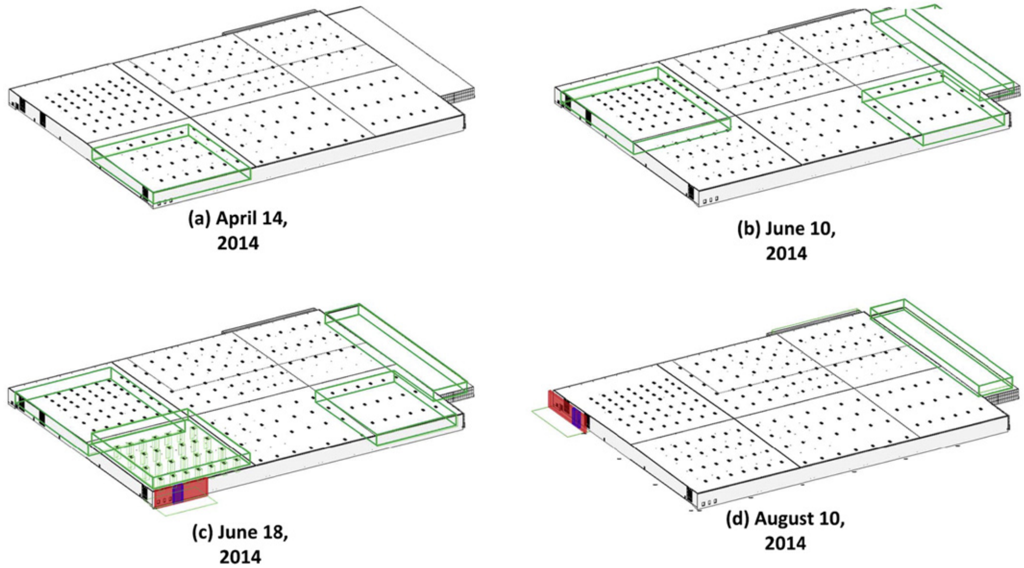


Fig. 17. Workspaces, scaffolding spaces generated during BIM-safety simulation.

monitoring participated in the case study assessment. The safety manager participated in a thorough review of daily construction condition simulation and hazard detection with construction managers. According to the review of the results, many of the potential hazards found from simulation were not identified or even discussed by the construction and safety managers. "Falling objects to scaffolds from activities above" were detected many times from the construction plan. In Fig. 18, the masonry crew using the scaffolds is under the risk of falling objects from both roofing and skylight installation activities. In particular, the work zone in Fig. 20 shows a situation that requires attentions by construction and safety managers. Potential of multiple safety hazards were detected from activities around the work zone.

- Spatial conflict: The masonry wall construction crew (and a scaffolding) is sharing the same space with a roofing crew on the same level.
- Falling objects from above: Both roofing and masonry crew on the same level are exposed to falling objects from roofing and skylight installation activities above.

Manual safety planning actually conducted by the safety managers did not identify the work zone to be a high risk area needing particular attention. The construction and safety managers agreed that these situations could become hazardous to the crews depending on the construction methods. For example, if the roofing crew handles heavy materials and equipment without knowing the locations of masonry crew and scaffolds, falling objects can directly injure workers or damage the scaffolds that possibly threaten the workers. It has also been discussed that the possibility of accidents can potentially be reduced by the increased situation awareness if this result is communicated by superintendents and related subcontractors before they start daily tasks.

Finally, the safety hazards identified during the simulation were summarized automatically. While the summary exists in the user interface, a schedule of identified hazards was automatically created to assist in effective safety communication as shown in Fig. 21.

6. Discussions and conclusions

This paper presented a framework and algorithms to integrate temporary structures to the automated safety analysis. While previous efforts in computer-assisted safety planning did not account for temporary structures, the developed BIM-safety simulation platform integrated scaffolds and spatial movements of crews using the scaffolds as an essential part of automated safety analysis. Eventually, this platform combines work plans of multiple subcontractors and detects potential safety hazards. The results show that the hazard detection algorithms

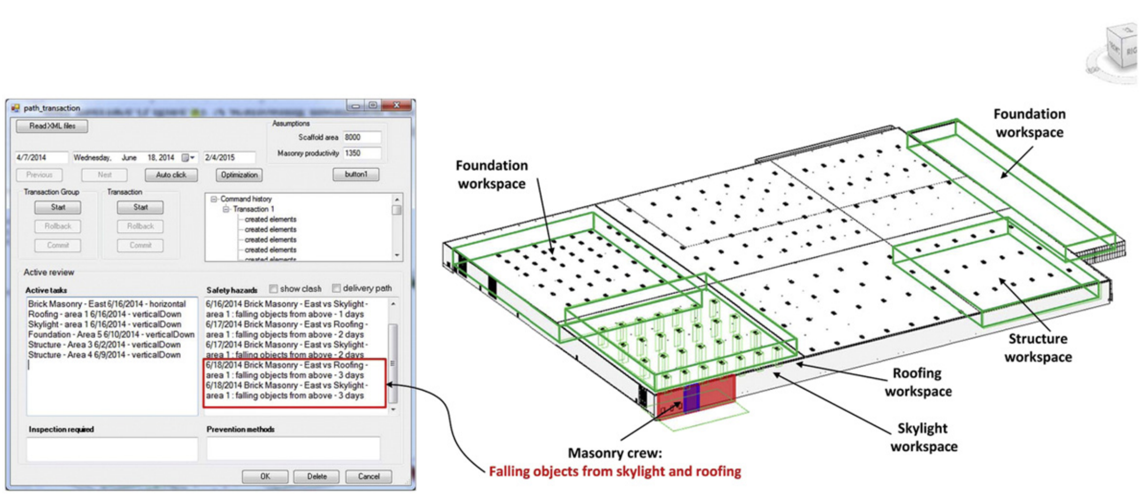


Fig. 18. User interface with potential safety hazard list and site condition visualization.

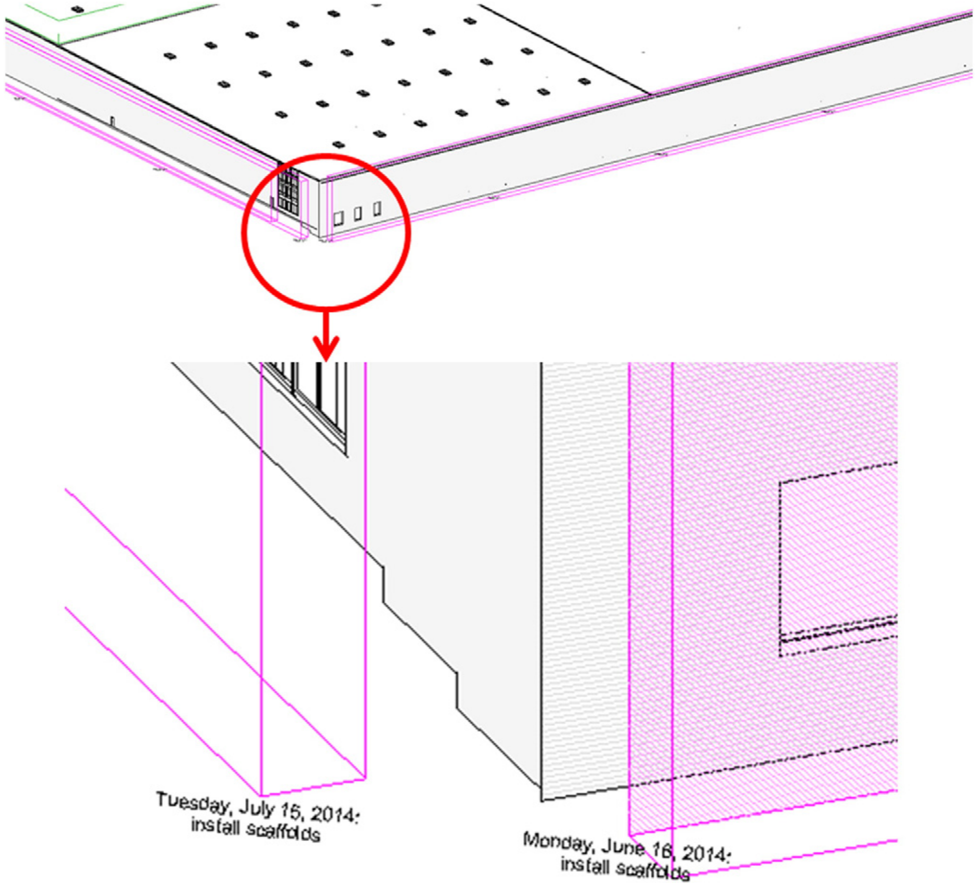
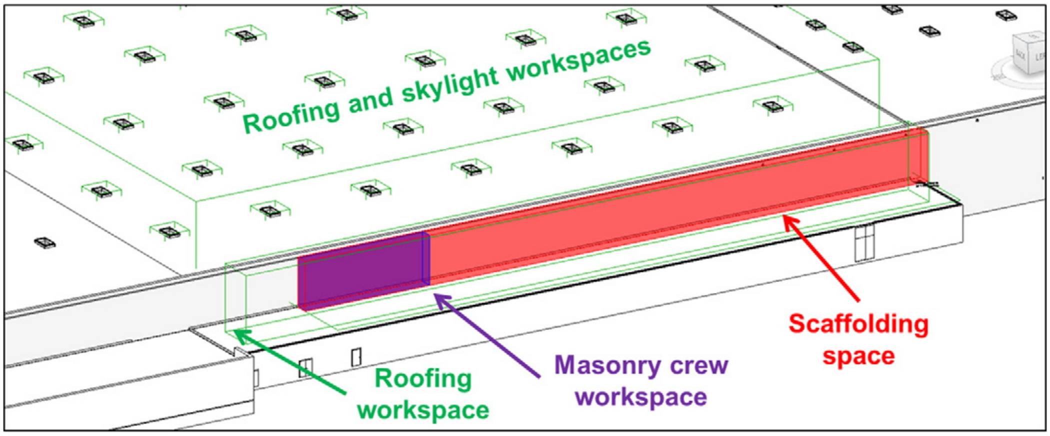


Fig. 19. Scaffolding installation schedule visualization.

can identify safety hazards that were not noticed by project and safety managers participating in the case study. Furthermore, this study successfully demonstrated that the construction visualization incorporating workspaces and temporary structures and the hazard schedule as an example of result reporting can potentially facilitate timely safety communications by construction and safety managers.

The unique contributions and impacts of this research are discussed. Direct impacts are: (1) As validated in the case study, our automated system detected unsafe conditions that were not recognized by safety managers of the project. Therefore, as a second-layer of safety detection tool, the proposed approach can assist construction and safety managers to prepare preventive actions early in the planning stages. (2) Our algorithm automatically generates the detailed schedule for scaffolding installation which is not shown in the original contractor's schedule program. (3) The detailed safety hazard schedule created by our system will assist the safety/project manager to focus on the recognized potential hazards on daily basis. Potential impacts are: (1) Our system can potentially provide the functions which not only identify safety hazards but also provide preventative solutions for them. (2) Safety communications (between superintendents, safety managers, inspectors, and workers) can be facilitated using hazard schedules and hazard visualization regarding temporary structures. (3) More effective safety training can be provided to workers using the hazard visualization and reports that incorporate temporary structures. (4) All these eventually contribute to the creation of safe construction plans that minimize worker's exposure to safety hazards.

While the test results were promising, several limitations of the prototype were recognized. (1) Hazard identification using the three rules may not identify all the potential safety hazards in current status. Since the three rules use only workspaces and scaffolding objects as the input, potential safety hazards related to activities out of the workspace (such as material delivery and movement out of the workspace) cannot be detected. In order to identify the out-of-workspace hazards, movements and material delivery paths need to be modeled and used as input for the safety analysis. (2) Another limitation of the hazard identification is that the characteristics (such as tools and materials) of the activities have not been considered within the three rules. In the case study, roofing and skylight installation tasks involved utilization of heavy materials and tools that can cause injuries due to falling objects. However, other tasks like painting and cleaning may expose workers to minimum safety risks. For more realistic hazard recognition, construction tasks need to contain information on their potential impact on safety. (3) The focus on activities with path plans (e.g. masonry wall construction) for daily workspace creation may over-simplify the details of other activities (e.g. roofing and skylight). This problem can potentially be overcome by applying predefined patterns. However, comprehensive creation of daily work details may need a comprehensive investigation into the behaviors and spatial flows of those activities. (4) Also, the current path creation mechanism requires a user to specify work paths of crew manually. When we consider more complex building geometric conditions, there needs to be an additional automation method to assist users to generate work paths based only on the directions of the crews. For example, a work package of a masonry crew can comprise multiple walls that are not aligned straight. In such case, the path creation presented in this paper needs multiple times of user input which is labor intensive. (5) The implementation and case study in this paper focused on supported scaffolds used by masonry crews only. To apply the proposed approach to more complicated construction projects, various types of scaffolds, such as suspended scaffolds and mast climber, need to be added in the system.



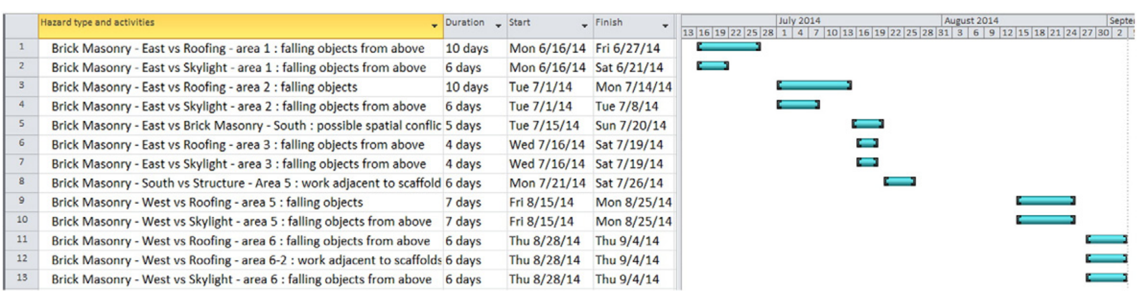
Hazard list

Hazard 1
Time: 8/28/2014 – 9/4/2014
Related activities: "Masonry wall 2nd floor" and "Roofing area 1"
Hazard description: Falling objects from roofing to masonry crew

Hazard 2
Time: 8/28/2014 – 9/3/2014
Related activities: "Masonry wall 2nd floor" and "Roofing area 2"
Hazard description: Spatial conflict between masonry and roofing crews

Hazard 3
Time: 8/29/2014 – 9/1/2014
Related activities: "Masonry wall 2nd floor" and "Skylight installation"
Hazard description: Falling objects from above to masonry crew

Fig. 20. Safety hazards identified in a high risk area.



	Hazard type and activities	Duration	Start	Finish
1	Brick Masonry - East vs Roofing - area 1 : falling objects from above	10 days	Mon 6/16/14	Fri 6/27/14
2	Brick Masonry - East vs Skylight - area 1 : falling objects from above	6 days	Mon 6/16/14	Sat 6/21/14
3	Brick Masonry - East vs Roofing - area 2 : falling objects	10 days	Tue 7/1/14	Mon 7/14/14
4	Brick Masonry - East vs Skylight - area 2 : falling objects from above	6 days	Tue 7/1/14	Tue 7/8/14
5	Brick Masonry - East vs Brick Masonry - South : possible spatial conflic	5 days	Tue 7/15/14	Sun 7/20/14
6	Brick Masonry - East vs Roofing - area 3 : falling objects from above	4 days	Wed 7/16/14	Sat 7/19/14
7	Brick Masonry - East vs Skylight - area 3 : falling objects from above	4 days	Wed 7/16/14	Sat 7/19/14
8	Brick Masonry - South vs Structure - Area 5 : work adjacent to scaffold	6 days	Mon 7/21/14	Sat 7/26/14
9	Brick Masonry - West vs Roofing - area 5 : falling objects	7 days	Fri 8/15/14	Mon 8/25/14
10	Brick Masonry - West vs Skylight - area 5 : falling objects from above	7 days	Fri 8/15/14	Mon 8/25/14
11	Brick Masonry - West vs Roofing - area 6 : falling objects from above	6 days	Thu 8/28/14	Thu 9/4/14
12	Brick Masonry - West vs Roofing - area 6-2 : work adjacent to scaffolds	6 days	Thu 8/28/14	Thu 9/4/14
13	Brick Masonry - West vs Skylight - area 6 : falling objects from above	6 days	Thu 8/28/14	Thu 9/4/14

Fig. 21. A schedule of potential hazards.

Future research may overcome the discussed limitations and attempt more pragmatic safety and productivity analysis by integrating important construction site components, such as stair towers and material storage areas. For example, the locations of stair towers and storages areas may be analyzed and optimized to ensure short material delivery paths to the workspaces. Further improvements can be achieved by optimizing the construction planning decisions made by general contractors and subcontractors. A set of assumptions was made for the simulation in this research. The optimization in the future research can automatically apply various crew and temporary structure settings to generate a set of solutions with optimum performances in terms of safety and productivity. Different number of crews, scaffolding installation quantity, and directions of work paths are examples of optimization parameters that are expected to be adjusted automatically in the future research. In addition, a future study can integrate wireless sensor technologies to the BIM safety system to track locations of onsite workers for real-time safety monitoring.

References

[1] OSHA, Commonly Used Statistics, https://www.osha.gov/oshstats/commonstats.html2014 (accessed January 17, 2015).

[2] BLS, Fatal Occupational Injuries by Event or Exposure for All Fatalities and Major Private Industry Sector, All United States, http://www.bls.gov/iif/oshwc/cfoi/cftb0249.pdf2009 (accessed January 17, 2015).

[3] S.M. Whitaker, R.J. Graves, M. James, P. McCann, Safety with access scaffolds: development of a prototype decision aid based on accident analysis, J. Saf. Res. 34 (2003) 249–261, http://dx.doi.org/10.1016/S0022-4375(03)00025-2.

[4] V.K. Bansal, Application of geographic information systems in construction safety planning, Int. J. Proj. Manag. 29 (2011) 66–77, http://dx.doi.org/10.1016/j.ijproman.2010.01.007.

[5] S. Zhang, J. Teizer, J.K. Lee, C.M. Eastman, M. Venugopal, Building information modeling (BIM) and safety: automatic safety checking of construction models and schedules, Autom. Constr. 29 (2013) 183–195, http://dx.doi.org/10.1016/j.autcon.2012.05.006.

[6] M. Behm, Linking construction fatalities to the design for construction safety concept, Saf. Sci. 43 (2005) 589–611, http://dx.doi.org/10.1016/j.ssci.2005.04.002.

[7] R. Ratay, Temporary structures in construction operations, Proc. a Sess. Spons. By Constr. Div. Am. Soc. Civ. Eng. Conjunction with ASCE Conv. Atl. City 1987, pp. 1–8.

[8] R. Ratay, Handbook of Temporary Structures in Construction, McGraw-Hill Professional, 1996.

[9] OSHA, Top 10 Most Frequently Cited Standards, https://www.osha.gov/Top_Ten_Standards.html2014.

[10] OSHA, Scaffolding eTool, https://www.osha.gov/SLTC/etools/scaffolding/overview.html2003 (accessed January 17, 2015).

[11] K.M. Halperin, M. McCann, An evaluation of scaffold safety at construction sites, J. Saf. Res. 35 (2004) 141–150, http://dx.doi.org/10.1016/j.jsr.2003.11.004.

[12] A. Suraji, A. Duff, S. Peckitt, Development of causal model of construction accident causation, J. Constr. Eng. Manag. 127 (2001) 337–344, http://dx.doi.org/10.1061/(ASCE)0733-9364(2001)127:4(337).

[13] J. Kim, M. Fischer, J. Kunz, R. Levitt, Semiautomated scaffolding planning: development of the feature lexicon for computer application, J. Comput. Civ. Eng. (2014).

[14] K. Kim, J. Teizer, Automatic design and planning of scaffolding systems using building information modeling, Adv. Eng. Inform. 28 (2014) 66–80.

[15] OSHA, A Guide to Scaffolding Use in the Construction Industry, https://www.osha.gov/Publications/osha3150.pdf2002 (accessed January 17, 2015).

[16] Nemetschek, Scia Scaffolding: Providing an Accurate Design and Time-Saving Workflow, (n.d.). http://www.scia-online.com/www/websiteUS.nsf/0/e87baaf3b09f3439c125758a004a411a/$FILE/Scia-Scaffolding.pdf (accessed January 17, 2015).

[17] Smart Scaffolder, Exploit the benefits of BIM (Building Information Modelling)ss, (n.d.). http://www.smartscaffolder.com (accessed January 17, 2015).

[18] K. Sulankivi, K. Kähkönen, 4D-BIM for Construction Safety Planning, Proc. W099- …. 2010, p. 117 (http://cibworld.xs4all.nl/dl/publications/w099_pub357.pdf#page=122).

[19] R. Jongeling, J. Kim, M. Fischer, C. Mourgues, T. Olofsson, Quantitative analysis of workflow, temporary structure usage, and productivity using 4D models, Autom. Constr. 17 (2008) 780–791, http://dx.doi.org/10.1016/j.autcon.2008.02.006.

[20] B. Akinci, M. Fischer, J. Kunz, Automated generation of work spaces required by construction activities, J. Constr. Eng. Manag. 128 (2002) 306–315, http://dx.doi.org/10.1061/(ASCE)0733-9364(2002)128:4(306).

[21] S. Zhang, B. Frank, T. Jochen, Ontology-based semantic modeling of construction safety knowledge: towards automated safety planning for job hazard analysis (JHA), Autom. Constr. 52 (2015) 29–41.

[22] H. Moon, N. Dawood, L. Kang, Development of workspace conflict visualization system using 4D object of work schedule, Adv. Eng. Inform. 28 (2014) 50–65, http://dx.doi.org/10.1016/j.aei.2013.12.001.

[23] CPWR, The Construction Chart Book, fifth ed. Center for Construction Research and Training, Silver Spring, MD, 2013.

[24] Construction Industry Institute, Playbook of Leading Industry Practices for Estimating, Controlling, and Managing Indirect Construction Cost, 2012.