AUTOMATED TEMPORARY STRUCTURE SAFETY PLANNING USING BUILDING INFORMATION MODELING (BIM)

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AUTOMATED TEMPORARY STRUCTURE SAFETY PLANNING USING BUILDING INFORMATION MODELING (BIM)

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Dedicated to my mother, father, sister, and fiance for their unwavering support.

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TABLE OF CONTENTS

ACKNOWLEDGEMENTS . . . . **iv**

LIST OF TABLES . . . . **ix**

LIST OF FIGURES . . . . **x**

SUMMARY . . . . **xiii**

I INTRODUCTION **1**

- 1.1 Construction safety planning 1
- 1.2 Current status of planning temporary structures 2
- 1.3 Current status of planning scaffolds 4

II RESEARCH GOAL AND OBJECTIVES **6**

- 2.1 Research goal 6
- 2.2 Research objectives 6
  - 2.2.1 Objective 1: Temporary structure object creation in BIM for safety planning 7
  - 2.2.2 Objective 2: Automated identification of potential safety hazards related to temporary structures 9
  - 2.2.3 Objective 3: Temporary structure plan optimization 10

III LITERATURE REVIEW **12**

- 3.1 Computer-assisted approaches of temporary structure planning . . . 12
- 3.2 Point of departure: the need for an automated system for temporary structures 16

IV METHODOLOGY **18**

- 4.1 Objective #1: Temporary structure object creation in BIM for safety planning 18
- 4.2 Objective #2: Automated identification of potential safety hazards related to temporary structures through safety simulation 19
- 4.3 Objective #3: Temporary structure plan optimization by case enumeration, manual selection, and refinement 19
- 4.4 Validation of research 20

V AUTOMATED PLACEMENT OF SCAFFOLDING IN BIM . . 21
5.1 Introduction . . . 21
5.2 Objective and scope . . . 22
5.3 Framework for automated scaffolding placement . . . 22
5.4 Development of Scaffolding Placement Engine . . . 23
5.4.1 Overview . . . 23
5.4.2 Details to the development of Scaffolding Placement Engine . 26
5.5 Implementation of scaffolding placement algorithms . . . 45
5.6 Conclusions and discussion . . . 50
VI AUTOMATED CHECKING OF SCAFFOLDING-RELATED SAFETY HAZARDS IN BIM . . . 51
6.1 Introduction . . . 51
6.2 Objective and scope . . . 53
6.3 Development of BIM-based safety analysis automation . . . 54
6.3.1 Framework of BIM-based safety analysis automation . . . 54
6.3.2 Technical details of BIM-safety platform . . . 56
6.4 Case study for validation . . . 72
6.5 Discussions and conclusions . . . 78
VII OPTIMIZATION OF SCAFFOLDING PLAN FOR SAFETY . . 80
7.1 Introduction . . . 80
7.2 Objective and scope . . . 83
7.3 Development of the proposed scaffolding optimization engine . . . 84
7.4 Implementation and case study . . . 90
7.5 Results and discussion . . . 103
VIII VALIDATION OF SCAFFOLDING PLACEMENT, SAFETY PLANNING, OPTIMIZATION . . . 105
8.1 Case study introduction . . . 105
8.2 System preparation for simulation and optimization . . . 108
8.2.1 4D BIM preparation . . . 108

8.2.2 Optimization input preparation 111

8.2.3 Objective functions 116

8.3 Implementation results 118

8.3.1 Scaffolding placement 118

8.3.2 Scaffolding-related hazard recognition 119

8.3.3 Enumerative generation of scaffolding plan alternatives . . . 121

8.3.4 Performance-based selection and review in 4D BIM 121

8.3.5 Selection of final scaffolding plan 126

8.4 Conclusions and discussion 126

IX CONCLUSIONS AND LIMITATIONS 128

9.1 Summary of works performed 128

9.2 Contributions and impacts 129

9.3 Limitations and future research 130

REFERENCES 132

VITA 136

LIST OF TABLES

1 Computer-assisted approaches for temporary structure planning (M: manual, I: insufficiently automated, A: automated) 15

2 Scores for different hazard types 93

3 Safety hazard score calculation functions 117

LIST OF FIGURES

1 Framework for proposed research on temporary structure safety planning 7
2 Framework for BIM-based scaffolding placement 24
3 Identified scaffolding design and planning workflow 28
4 A general contractors masonry wall paths in a real construction project 30
5 Geometric features recognized to plan scaffolding for a short masonry wall 32
6 Geometric features recognized to plan scaffolding for a large masonry wall package 32
7 Simplified representation of a scaffolding object 34
8 Scaffolding objects associated with schedule information 35
9 Design details created in a scaffolding space 36
10 Scaffolding placement process 37
11 Shape of a scaffolding space 39
12 Analytical view of scaffolding and workspace 42
13 Masonry walls and user-defined work directions 43
14 Plane-face intersection for each inspection point 44
15 Plane-face intersections of rectangular walls 46
16 Plane-face intersections of walls with varying heights 46
17 Scaffolding and workspace instances created along the path 47
18 Daily workspaces created along the work direction 48
19 Scaffolding space created based on maximum work face heights 48
20 Scaffolding objects and workspaces incorporated into day 3 of 4D BIM 49
21 Scaffolding objects and workspaces incorporated into day 5 of 4D BIM 49
22 Framework for automated BIM-safety platform 55
23 BIM-safety platform system architecture 57
24 BIM-safety platform system architecture 58
25 Workspace generation for activities 60

26 Automated detail generation based on input work sequence and assumptions 62
27 Scaffolding space, workspace, and limited access zones 62
28 4D BIM with on-going construction tasks highlighted 63
29 Workspace generation for the building model 64
30 4D BIM with spatial information integrated 64
31 Daily workspace movement and scaffolding installation 65
32 Conflict between a workspace and a scaffolding space 67
33 Falling objects from scaffolding 68
34 Falling objects to scaffolding 69
35 Safety simulation graphical user interface 71
36 BIM for a real building construction project 73
37 Zoning and work path plans 73
38 Workspaces, scaffolding spaces generated during BIM-safety simulation 74
39 User interface with potential safety hazard list and site condition visualization 75
40 Scaffolding installation schedule visualization 75
41 Safety hazards identified in a high risk area 77
42 A schedule of potential hazards 78
43 Framework of the proposed Scaffolding Optimization Engine 84
44 Work paths planned for three masonry construction tasks using scaffolding 86
45 An example of scaffolding planning seed 87
46 Workflow of the proposed scaffolding optimization engine 89
47 Schedule and task detail setup 92
48 Hazard type 1 and type 2 94
49 Hazard type 3 94
50 Hazard type 4 and type 5 95
51 Hazard type 6 96
52 Options and objective values of 144 scaffolding alternatives 97

53 144 scaffolding plan alternatives in duration-cost plot 98
54 3D scatterplot of 144 scaffolding plan alternatives 99
55 Performance-based selection of alternatives 101
56 Original schedule with detected unsafety zones visualized 102
57 Scheduling alternative 69, 138, and 140 with detected unsafety zones visualized 102
58 Scheduling alternative 43, 46, and 114 with detected unsafety zones visualized 103
59 Building model of five-story campus residential building 106
60 Original construction sequences for structural parts 107
61 Sequence for building skin construction 108
62 Scaffolding location line input 109
63 Work zones specified in the original construction plan 110
64 Partitioning of work zones for the safety simulation 110
65 Scaffolding placement with width limitation 112
66 Sequences for one crew for Building A and Building B option 113
67 Reversed task order option 114
68 Reversed paths in a task 115
69 Reversed structural sequences 115
70 Result of plane-face intersection analysis 118
71 Mast climber scaffolding and structural work zones in 4D BIM 119
72 Report and visualization of entire safety hazards 120
73 Hazard visualization in 4D environment 120
74 Graphic user interface of optimization 121
75 Five alternative scaffolding plans were selected based on the performances 123
76 Sequence and safety hazard highlights of original plan 124
77 Scaffolding plan summary for alternative 1 and 2 124
78 Scaffolding plan summary for alternative 3 and 4 125
79 Scaffolding plan summary for alternative 3 and 4 125

SUMMARY

The primary objective of this research is to create and test a framework to assist in the creation of temporary structure plans that are executable and optimized for safety. Temporary structures, such as scaffolding, formwork, and shoring, are frequently used in construction sites impacting the safety of workers and the entire construction project. However, temporary structures are often installed in construction sites without sufficient consideration on their impacts on safety. One of the major causes of the problem is heavy reliance on manual efforts and subjective judgment of engineers in planning and managing temporary structures. Due to complex and changing nature of construction, it can be extremely challenging to manually plan and analyze temporary structures. Capabilities of existing technologies, such as Building Information Modeling (BIM) and temporary structure designing software tools, are limited to creatiing and visualizing temporary structures. Thus, it can be seen that there is a need for an approach that can assist in front-end planning, analysis, and optimization of temporary structures in a way that the reliance on manual efforts is reduced and eventually overall safety can be improved.

This research integrates temporary structures in BIM, analyzes their impact on safety, and optimizes the original temporary structure plan into a safer plan. The scope of temporary structures is limited to scaffolding that provides elevated work platform for construction activities. Automation algorithms were created and tested in real-world construction projects. The validation demonstrated that the proposed approach can contribute to the creation of safe construction plans by automatically planning, analyzing, and optimizing temporary structures.

CHAPTER I

INTRODUCTION

The intent of this chapter is to introduce an overview of the status of safety hazards occuring in construction industry, safety planning practices, and safety issues related to temporary structures. Existing drawbacks and research needs are derived from this chapter.

1.1 Construction safety planning

Construction is considered as a hazardous industry that can potentially expose workers to fatal hazards. According to the Occupational Safety and Health Administration (OSHA), the construction industry is responsible for 796 (more than 20%) incidents out of 3,929 worker fatalities in the US private industry [31]. Falls from elevation, struck by objects, electrocutions, and caught-in/between are among the leading causes of fatal hazards. Accidents related to temporary structures also account for a large proportion of the causes of the safety hazards. In 2009, there were 54 fatalities from scaffolding and staging [5]. Especially, falls from scaffolds form one of the leading causes of the entire fall fatalities and injuries [42]. Besides falling, improper planning and usages of scaffolds can cause other types of hazards, such as falling objects from scaffolds, electrocution, and spatial conflicts with construction activities.

It is optimal in safety planning and management to identify most of the potential safety hazards early in the design and planning stages and prepare preventive measures. However, actual safety planning practices in the construction industry have several drawbacks that prohibit effective front-end safety planning. Currently, construction safety planning is often conducted separately from the earlier planning efforts [3]. 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 construction plans. Secondly, construction jobsite hazard analysis (JHA) and pretask planning rely 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 [44]. Currently, the cooperation and communication among project stakeholders related to safety is still limited [4].

1.2 Current status of planning temporary structures

Safety planning becomes even more challenging when temporary structures are considered. Temporary structures are structures used to assist in the construction of the permanent part of a construction project. Common examples include scaffolding, formwork, shoring systems, etc. Most construction projects frequently utilize several types of temporary structures. The entire construction safety, quality, speed, and profitability are impacted by how temporary structures are used [34]. Temporary structures can cause spatial and temporal conflicts between other temporary structures or workspaces which then can lead to unsafe site conditions and loss of productivity [2]. According to Ratay [35], many construction disasters occur due to the failures of temporary structures during construction. The Construction Industry Institute (CII) highlighted in a recent research study that temporary structures form one of the top four primary cost categories belonging to indirect construction costs which deserve more attention [11].

Despite the significant impact of temporary structures on a construction project, existing safety planning practices fail to effectively address safety problems associated with temporary structures. First, temporary structures lack effective front-end planning and management. Architectural drawings, bid drawings, BIM, and construction schedules typically do not include plans for temporary structures except for exceptionally complex temporary structures, such as cofferdams [18,34]. Due to the lack of time and understanding, calculations and drawings of temporary structures submitted by temporary structure subcontractors are reviewed only to assess the impacts on the permanent part of the building [34]. Considering the reality of most construction projects that are short of human resources for construction planning [17], the manual processes of modeling temporary structures in BIM and detecting/addressing all related potential safety issues can be extremely labor-intensive.

Along with the lack of front-end planning and management, the current industry practices suffer from heavy reliance on the knowledge and experiences of individual engineers. 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. While software programs exist that are specialized in designing temporary structures (e.g., formwork, scaffolding), mostly they focus on creating detailed designs of temporary structures. In current construction and safety planning practices, negative impacts of temporary structures on safety can only be minimized by manual construction site condition analysis of individual engineers. Due to potentially imperfect human judgment, there exist chances of making erroneous decisions related to temporary structures.

As it will be discusses in the literature review section, capabilities of existing state-of-the-art technologies are often limited to generating temporary structure designs and visualizing them. They are lack of capabilities to automatically analyze construction site conditions and identify potential safety hazards associated with the temporary structures. Therefore, the reliance on error-prone manual efforts remains the same even with utilization of visualization technologies. Taking into account the importance of temporary structures and the deficiencies of the current industry practices and technology in addressing associated safety issues, there is a need for advanced approaches that enable automated safety planning for temporary structures in a way that reduce the reliance on manual efforts. There is also a need for approaches to refine and optimize a temporary structure plan into a safer and more productive temporary structure plan.

1.3 Current status of planning scaffolds

Among various types of temporary structures, there are wide-spread concerns over safety hazards associated with scaffolds. Scaffolds are also insufficiently planned, procured, and managed in construction projects. Safety regulations related to scaffolds are still one of the most frequently violated regulations [32]. According to OSHA, approximated 65% of the construction workers are frequently on scaffolding systems. Preventing accidents associated with scaffolds can exclusively protect workers from about 4,500 injuries and 50 deaths annually. Proper scaffolding design and construction planning has the potential to prevent American employers spending annual $90 million on lost workdays [30]. These statistics indicate that there is a need for enhanced methods and tools for temporary structure safety planning, especially related to 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 [15, 30]. However, occurrences of safety hazards can be more strongly tied to underlying causes, such as inappropriate construction planning, inappropriate construction control, inappropriate construction operation, etc [40]. Similarly, safety hazards related to temporary structures can be triggered as a result of unsuccessful safety planning and management [42]. Simple safety and inspection checklist tools widely used today are not effective in addressing safety problems in the early design and planning stages [42].

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 research integrates capabilities of temporary structure object creation, automated safety checking, and optimization into BIM. Core computational algorithms developed in this research identify safety hazards associated with temporary structures automatically by analyzing project information contained in BIM and schedule. This research focuses on planning of scaffolds due to their frequent uses in construction and wide-spread concerns over scaffold-related safety hazards.

CHAPTER II

RESEARCH GOAL AND OBJECTIVES

This chapter defines the research goals and specific objectives. For each objective, research questions, scope, and expected deliverables are discussed.

2.1 Research goal

The goal of this research is to create and test a framework to assist in the creation of temporary structure plans that are executable and optimized for safety.

2.2 Research objectives

To achieve the research goal, three research objectives related to temporary structure planning, analysis, and optimization were formulated as illustrated in Figure 1.

- **Planning**: The first objective is to identify workflows of planning temporary structures to automatically create temporary structures.

- **Analysis**: The second objective is to define temporary structure safety hazards and create methods to automatically detect the potential safety hazards.

- **Optimization**: The third objective is to define a process to assist in the decision making to create optimal temporary structure plans.

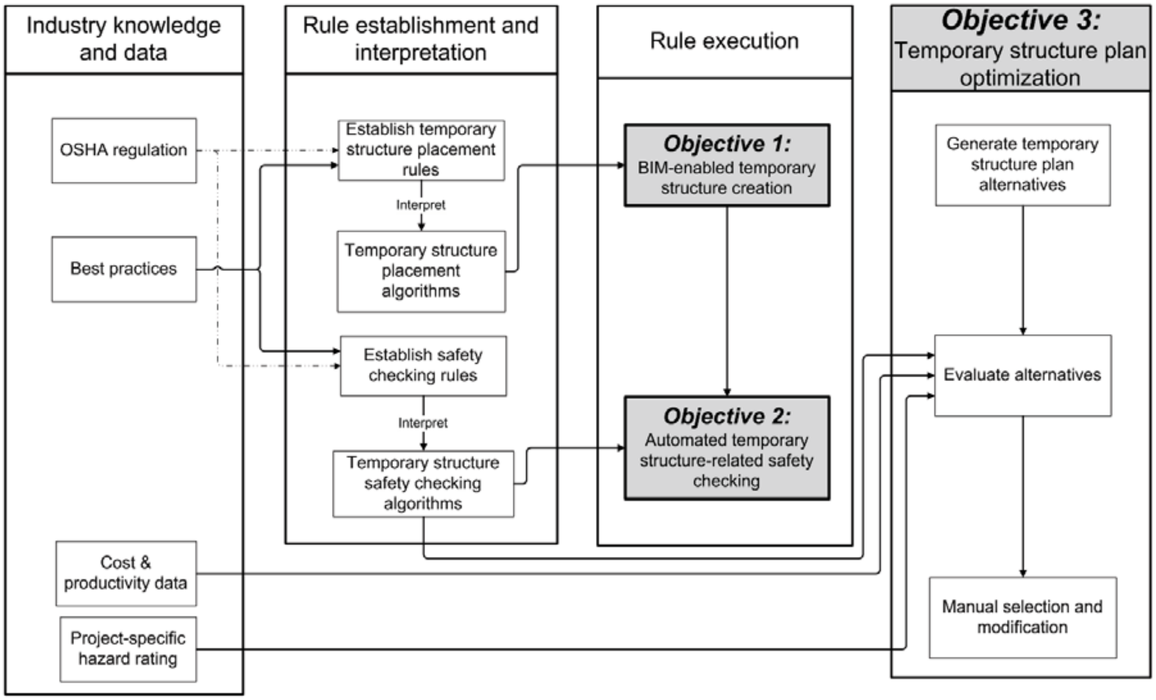


Figure 1: Framework for proposed research on temporary structure safety planning

2.2.1 Objective 1: Temporary structure object creation in BIM for safety planning

The first objective of this research is to enable the creation of temporary structure objects in BIM that can be used for computer-driven tasks, such as automated construction safety analysis and optimization. Related research questions are:

1. *How are temporary structures planned in practice? How are potential safety hazards identified?*
2. *How can temporary structures be planned as part of a construction plan? How can the process be automated?*

Currently available BIM and construction planning technologies have highly limited capabilities to assist in temporary structure planning and detection of associated safety hazards. While temporary structure objects can be inserted into BIM and 4D BIM for visualization and quantity takeoff, incidents of potential safety hazards caused by temporary structures can only be identified by labor-intensive manual analysis of engineers. Similarly, refinements to the temporary structure plan to achieve greater safety can also be made relying on manual efforts of trial-and-error.

In order to address the drawbacks, this research enables automated creation of temporary structure objects in BIM. Industry knowledge in construction and safety is embedded into the process of creating temporary structure objects in BIM. Creation of detailed temporary structure designs will be not included in the scope of the research. This research attempts to address safety hazards that can be prevented through better placement of temporary structures and construction site coordination, rather than accurate designs. Significant progresses have already been made regarding automated creation of design details of temporary structures [21,25,38]. In real-world applications, incorporating the detailed temporary structure designs and utilizing them for benchmark for installation and inspection would make the safety management using BIM more comprehensive. In this research, important features of temporary structures impacting construction safety, such as basic shapes and locations of temporary structure, will be incorporated. Also, the types of temporary structures will be limited to scaffolding due to widespread concerns on scaffolding safety and current lack of planning efforts.

The deliverables of this objective include (1) information requirement for scaffolding objects, (2) scaffolding placement process in human language and (3) its translation into computational algorithms. The scaffolding information requirement explains a scaffolding object's information needed for scaffolding visualization, placement, and safety analysis in BIM. The scaffolding placement process is a structured description on how scaffolds are planned by the practitioners. The scaffolding placement algorithms are algorithms that implement the logic of the placement process in BIM and

4D BIM. By applying the developed algorithms, temporary structure objects can be integrated into BIM and construction schedule in a way that can be used for further analysis and optimization.

2.2.2 Objective 2: Automated identification of potential safety hazards related to temporary structures

Even after inserting temporary structure objects in BIM and construction schedule, potential safety hazards related to temporary structures need to be identified without excessive manual efforts. Due to complex and changing construction environment, manual hazard recognition can be extremely labor-intensive and error-prone especially when temporary structures are considered. Since current industry practices and technologies do not present an effective method to analyze the impact of temporary structures on safety, many potential safety hazards are not identified in the construction planning stage. In order to address this deficiency, this research attempts to identify potential safety hazards related to temporary structures automatically in BIM. Related research questions are:

1. *What information is needed to identify potential safety hazards related to temporary structures?*
2. *How safety hazards can be defined for temporary structures?*
3. *How such definitions of safety hazards or safety knowledge can be used to automatically identify potential safety hazards?*

By answering this research question, potential safety incidents that occur related to temporary structures can be automatically detected. The deliverables of this objective include a set of scaffolding-related safety checking rules and computational algorithms that execute the rules. As a result of the analysis, a schedule of potential safety hazards can be automatically created. The generated safety hazard schedule with visualization in 4D BIM environment can provide detailed hazard information including location, time, and related crews of the hazards.

2.2.3 Objective 3: Temporary structure plan optimization

When establishing a plan for temporary structures, many decisions are made by stakeholders, such as general contractors, specialty contractors, and temporary structure subcontractors. For example, proper types of scaffolding, quantities of scaffolding installation at a time, and work directions of crews using scaffolding need to be decided. These decisions made in the planning stages can potentially impact the safety of the entire construction project. Therefore, there is a need to optimize the original temporary structure plan based on the results of safety analysis. In the optimization, factors other than safety, such as cost and duration, may need to be considered to support informed decision making. The third objective of this research is to optimize the original temporary structure plan into a safer plan without sacrificing other important goals. Related research questions are:

1. *What decisions are made when temporary structure plans are established? How can the decisions be made to ensure the temporary structure plans are safe and executable?*
2. *What criteria need to be considered in the optimization?*
3. *How can temporary structure plans quantitatively assessed based on the criteria?*
4. *What are the relationships among the criteria, such as cost, time and safety?*
5. *If the relationships are different by project by project, can a deterministic relationship be identified per project?*
6. *How can the relationships or tradeoffs among criteria used for decision making?*
7. *How optimal decisions can be flexibly made based on project-specific situations?*

By answering this research question, a temporary structure plan can be converted into an executable plan that minimizes worker exposures to potential safety hazards. The deliverables of this objective include a framework and computational algorithms for temporary structure optimization. Temporary structure-loaded BIM generated in the previous steps will be used as the input for this algorithm. As a result of applying the proposed optimization, an original temporary structure plan can be refined into a safer temporary structure plan.

CHAPTER III

LITERATURE REVIEW

Following section presents a review of current computer-assisted technologies in planning temporary structures. A point of departure was derived based on the learning from the literature review.

3.1 Computer-assisted approaches of temporary structure planning

Many approaches exist that take advantage of advanced information technology to assist in planning of temporary structures. In this section, existing computer-assisted approaches for planning temporary structures were reviewed to identify existing problems and limitations. In order to take advantage of the power of modern computers to plan temporary structures and address related safety hazards, it is desired that spatial-temporal conditions of construction sites are automatically analyzed without excessive human intervention. Currently, few approach automatically conducts such a reasoning task that analyzes spatial-temporal conditions in digital building models to assist in the creation and analysis of temporary structures. In most of the approaches, site condition analysis is manually conducted based on visual observation of 3D and 4D BIM. The safety management tool developed by Kim and Ahn [18] is one of few attempts that automatically analyze geometric information in BIM to automatically create scaffolding objects around the building perimeter. This research, however, did not present sufficient algorithm or systematic approach that can be used to analysis the spatial and temporal conditions. There are research studies that attempt to analyze buildings geometric conditions to assist in construction planning. [26] proposes a set of specialized queries to support construction planning. The queries include component intersection and penetration queries, locations queries, spacing queries, alignment queries, design uniformity queries, etc. However, most of their queries function in 2D geometry and under an assumption that building components (walls and columns) are aligned parallel with the x- or y-axis. Considering the alignments of building components that can vary depending on the design intents, their queries can be used to assess highly simple geometric conditions. Also, the queries have a limited potential to be extended to construction safety analysis. [44] presented a rule-based construction safety checking system focusing on fall protection. The safety planning system detects potential fall-related hazards from BIM models and suggests preventive actions. However, this research does not consider temporary structures as part of safety planning. Also, the safety planning system does not incorporate movements of work crews which is crucial for analyzing the site safety. [21] automatically analyzes the spatial relationships between wall faces and slab faces to automatically generate scaffolding objects in 4D BIM. This research focuses on identification of required scaffolding and creation of scaffolding designs according to safety regulations. [14] presented a BIM-based schedule optimization system that generates erection sequences considering cost, time, and jobsite movements. This research used stability relationships between building components to optimize erection sequences, it does not evaluate the impact of the decisions on worker safety.

Kim and Fischer [20] presents a theoretical foundation to enable automated scaffolding type selection. This research suggests a method to analyze the models geometric condition based on the relationship between the work face and the base surface. While their approach enables automated selection of temporary structure types, the work face and base surface of each situation should still be specified manually by a user. [37] developed an optimization tool for the aluminum formwork layout system with the objective of maximizing the area of standardized formwork elements compared to the area of customized formwork elements. The results show increased relative portion of standardized formwork elements compared to the customized elements. However, the main focus of analyzing the building geometry in this research is to optimize formwork designs. Furthermore, the major drawback of this system is the need for manual user input to specify corners of the formwork elements to recognize the geometric information of the building objects.

Some of other approaches support the generation of temporary structure designs automatically or manually. The tool developed by Kim and Ahn [18] automatically designs scaffolding systems around a building model perimeter. SmartScaffolder [38] automatically generates scaffolding systems of pre-defined types around walls. While these two approaches assist in users to generate scaffolding systems rapidly, they design scaffolding systems exclusively for walls and do not integrate scaffolding objects to construction schedules. Scia scaffolding [25] provides functions in its user-interface that assist users to design scaffolding systems manually. It also provides automated code-compliance and structural stability checking for scaffolding systems. Sulankivi et al. [39] and Kim and Ahn [18] incorporate safety features, such as guardrails, into the temporary structure models. Several approaches incorporate the temporary structure models into the main models and 4D construction simulations. Some of them used the temporary structure-loaded models and simulations for enhanced visualization and analysis of construction sites [16, 21]. Akinci et al. [2] specifies the space occupied by a scaffolding to analyze the spatial conflicts between spaces occupied by other construction activities or temporary structures.

Table 1: Computer-assisted approaches for temporary structure planning (M: manual, I: insufficiently automated, A: automated)

Objective	Areas of concern	Kim and Fischer [20]	Kim and Ahn [18]	Sulankivi et al. [39]	Akinci et al. [2]	Jongeling et al. [16]	Scia scaffolding [25]	SmartScaffolder [38]	Sattigari et al. [37]	**Proposed research**
Objective #1 Planning	Spatial-temporal condition analysis	M	I					I	M	A
	Temporary structure design generation	I	A	M		M	M	A	A	I
	Temporary structure type selection	A								
	Structural stability of temporary structures						A			
Objective #2 Analysis	Impact on safety			M	A	A				A
	Impact on productivity and duration					A				A
	Impact on cost							A	A	A
Objective #3 Optimization	**Possible when planning and analysis are integrated**									A

Table 1 summarizes the capabilities of existing approaches organized based on the objectives of this research. In general, it can be seen that there are few research study that enables automated analysis of spatial-temporal conditions to plan temporary structures and analyze associated safety hazards. On the other hand, several successful approaches were found that generate detailed designs of temporary structures. Even though certain types of safety hazards can be prevented by properly designing and inspecting temporary structures, this research aims to address potential safety hazards that can be prevented by better and systematic planning of temporary structures. Thus, generation of detailed temporary structure designs is not included in the scope of this research. Also, some of the research studies presented automated analysis of the impact of temporary structures on site safety and productivity. However, most of the analysis depend on manually created temporary structure plans or require extensive user input. To summarize, higher degree of automation in temporary structure planning and safety analysis is required to reduce excessive manual efforts. Also, planning and analysis of temporary structures need to be integrated systematically to enable computer-assisted optimization of temporary structure plans. Any of the reviewed computer-assisted approaches has not suggested a method to optimize temporary structure plans for safety.

3.2 Point of departure: the need for an automated system for temporary structures

Model-based technology, such as BIM, is considered as one of the solutions to improve construction and safety planning [13]. In many construction projects, temporary structures are integrated into the main building models to realistically visualize the construction progresses. However, the main benefit is often limited to visualization of the temporary structures. The crucial tasks for planning temporary structures and addressing associated safety problems have not taken full advantage of the advanced information modeling technology. They still rely on inefficient manual efforts. Remaining technical limitations are summarized as follows:

- Lack of systematic integration between temporary structure planning and analysis to enable temporary structure safety optimization
- Lack of methods to support decision making to create optimized temporary structure plans and minimize associated safety hazards
- Consequently, exhaustive trial-and-errors are still needed to create, analyze, modify temporary structure plans

Overall, current state of technology does not suggest a methodology that overcomes these drawbacks. Little research has been conducted to enable placement of temporary structure objects in BIM for computer-driven safety analysis using the temporary structure objects. Since planning and optimizing temporary structure utilization still requires experienced engineers to understand complex building geometry and schedule, potential exists to assist them for optimal decision making. Furthermore, an integrated tool that utilizes the rich and precise information available from digital building models, assesses the project conditions, and develops a safe and productive temporary structure plan automatically does not exist.

CHAPTER IV

METHODOLOGY

This chapter provides descriptions about the reserach methodologies for the three research objectives and validation of the research. In this research, the scope of temporary structures will be limited to scaffolding. Specific tasks to achieve each research objective are presented.

4.1 Objective #1: Temporary structure object creation in BIM for safety planning

The first objective of this research is to create temporary structure objects in BIM that can be used for computer-driven safety analysis and optimization. As a result, a prototype software program called "Scaffolding Placement Engine" is developed. Related tasks are:

1. **Establishing scaffolding placement process**: This research first identifies industry practices in planning scaffolds in construction projects. In-depth interviews with industry professionals, including general contractors, subcontractors, and scaffolding subcontractors, are conducted to identify a scaffolding placement process.

2. **Converting placement process into computer-readable algorithms**: The planning process is converted into computational algorithms for automated placement of scaffolding objects in BIM.

4.2 Objective #2: Automated identification of potential safety hazards related to temporary structures through safety simulation

This objective is to automatically identify potential safety hazards related to temporary structures (scaffolding) by analyzing daily construction site conditions. A prototype software program called "Safety Simulation Engine" is developed and tested in a real-world construction project. Related tasks are:

1. **Work path integration**: Spatial movements of crews using scaffolds are integrated into 4D BIM in order to account for dynamically changing spatial and temporal conditions in a construction iste.
2. **Space generation**: Various types of spaces, such as workspace, scaffolding space, scaffolding installation space, are integrated for automated safety analysis.
3. **Hazard identification and reporting**: For selected safety hazards, automated safety checking algorithms are developed. After identifying potential safety hazards in 4D BIM, the results are communicated by visual reports and a schedule of potential safety hazards.

4.3 Objective #3: Temporary structure plan optimization by case enumeration, manual selection, and refinement

Object 1 and 2 are expected to generate scaffolding objects in 4D BIM and detect potential safety hazards related to the scaffolding. The third objective of this research is to optimized the original scaffolding plan to achieve greater safety. "Optimization Engine" is developed and tested in a real-world construction project. As the optimization approach, this research uses following approach.

1. **Enumerative generation of alternative scaffolding plans**: Based on user-input for optimization, multiple alternatives of scaffolding plans are automatically generated by enumerating all the cases. Each alternative is quantitatively evaluated by the developed Safety Simulation Engine.
2. **Project-specific hazard weighting**: For quantitative evaluation of safety hazards, project-specific hazard weights are prepared.
3. **Performance-based selection and review**: The quantitative evaluations of the alternatives were used to select candidate plans for further review in 4D BIM environment.

4.4 Validation of research

This research will be validated by applying the developed software prototype to a scaffolding planning of a real-world construction project. The scaffolding utilization plan, site sequencing plans, BIM, and construction schedules have been obtained from the case study project. In the test, an original scaffolding plan created by the general contractor is used as the input for the automated safety analysis and optimization. Then, the scaffolding plans generated as a result will be compared with the original plan. As a result, it is expected that the proposed approach can create scaffolding plans that are safer than the original plan. In addition to project-specific hazard weighting, professional judgments of construction and safety managers of the project were used for comprison between alternative scaffolding plans.

CHAPTER V

AUTOMATED PLACEMENT OF SCAFFOLDING IN BIM

This chapter presents an automated placement of scaffolding objects in BIM. Based on in-depth interviews with industry professionals, a scaffolding placement process was identified and converted into computational algorithms for scaffoldign object creation in BIM. As a result, a prototype software program called "Scaffolding Placement Engine" was developed. The framework, methodology, and a case study are presented.

5.1 Introduction

Temporary structures are frequently used in most construction projects impacting the overall project safety and productivity. Among various types of temporary structures, scaffolding is considered as one of the most challenging and wasteful part of a construction project [10]. Despite the importance and prevalent concerns, safety regulations related to temporary structures, scaffolds especially, are still one of the most frequently violated safety regulations [31, 32]. Many worker fatalities and associated financial losses can be avoided by preventing accident related to scaffolding [30].

While there are safety regulations and industry practices related to scaffolding, most of the instructions are limited to requirements for design and inspection of elements of scaffolds, such as guardrails and boards. Few study has been conducted to figure out how to plan and analyze scaffolding as part of construction and safety plan. Previous studies indicate that many of direct causes of scaffolding accidents, such as missing guardrails and improper planking, can be triggered as a result of unsuccessful safety planning and construction management [42].

In current practices, scaffolding objects are not available in most construction project drawings, building models, and schedules. There have been research studies [39] that incorporate scaffolding objects into 4D BIM. Even though these approaches demonstrate the benefits of realistic visualization of scaffolding objects in BIM, potential safety hazards related to scaffolding need to be identified by manual observation of the digital construction models over the construction duration. Safety hazard recognition based on visual and manual observation can be inherently imperfect and highly dependent on subjective judgment of engineers. Possible human errors can lead to failures to recognize safety hazards related to scaffolds. While there are methods to take advantage of advanced BIM technology for automated safety hazard identification and prevention [44], there are few studies that incorporate temporary structures into the safety planning.

5.2 Objective and scope

The objective of this research is to enable the creation of temporary structure objects in BIM that can be used for automated safety hazard recognition and temporary structure plan optimization. An automated system called Scaffolding Placement Engine was developed. Based on BIM, construction schedule, and basic input from users, Scaffolding Placement Engine analyzes spatial-temporal conditions in a digital building model and creates scaffolding objects in BIM. Temporary structures will be limited to scaffolding used for masonry wall construction.

5.3 Framework for automated scaffolding placement

In order to minimize or remove human intervention, the Scaffolding Placement Engine conducts activities to plan scaffolds that are manually conducted these days. Therefore, the process for planning scaffolding needs to be identified first based on existing regulations and industry practices. The identified process is interpreted into computer-readable algorithms, and then the algorithms are embedded in BIM software program for automated placement of scaffolding objects. Three major tasks are:

- **Establishing scaffolding placement process**: Unlike explicit safety rules that are directly extractable from regulations, most of the process of planning temporary structures, including scaffolds, are conducted based on practices, implicit knowledge, and experience of practitioners. This task identifies the process of planning scaffolds and formulates the process into a scaffolding placement process in the form of natural language.
- **Defining scaffolding information requirements**: This research proposes an approach to use temporary structure objects in 4D BIM to enable automated safety planning and further optimization. Thus, the scaffolding objects need to contain information that is used to enable visualization, safety checking, and optimization of scaffolding. This task defines the information requirements based on the scaffolding placement process and further in-depth interviews with practitioners.
- **Converting placement process into computer-readable algorithms**: In order to assist in the creation of scaffolding objects that contain all necessary information without excessive manual efforts, the scaffolding placement process in human language need to be converted into computer-readable algorithms.

5.4 Development of Scaffolding Placement Engine

This section presents an overview of the proposed scaffolding placement and details about the development of the algorithms.

5.4.1 Overview

Figure 2 presents an overview of the scaffolding placement in BIM. By implementing the scaffolding placement algorithms, project information in BIM, construction schedules, and other user input can be analyzed automatically to create scaffolding objects. The scaffolding objects are expected to be linked to BIM and construction schedules properly so that they can be used for time-based visualization and analysis. Details to required steps of the development of Scaffolding Placement Engines are explained.

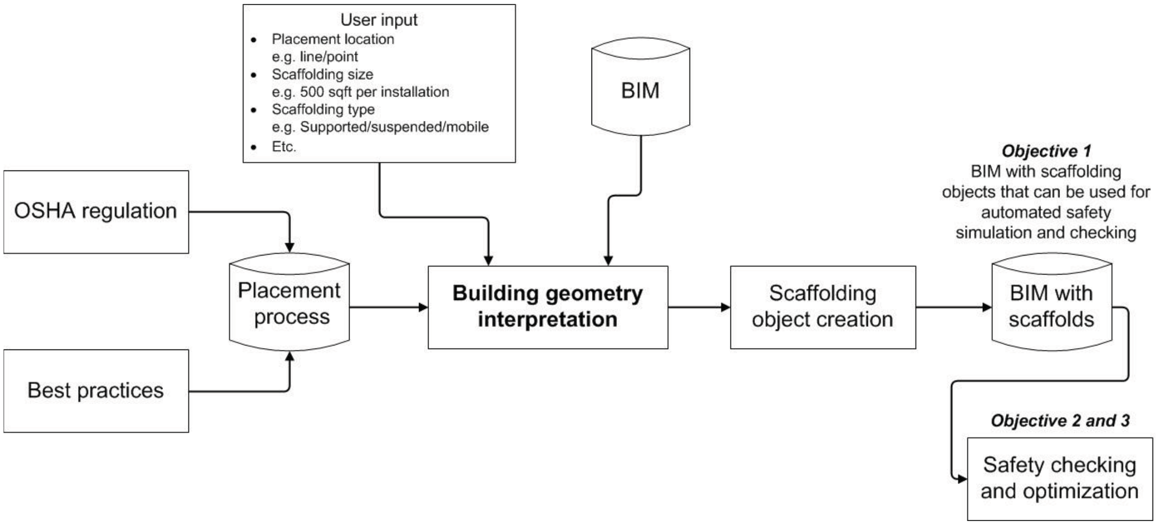


Figure 2: Framework for BIM-based scaffolding placement

1. ***Step 1: Analyze scaffolding-related practices and regulations***

   Many safety regulations provide explicit rules for safety checking. For example, the OSHA's construction fall protection rules contain explicit descriptions on how to analyze the site conditions (dimensions of holes) and how to prevent associated safety hazards (install fall protection system).

   "Hole means a gap or void 2 inches (5.1 cm) or more in its least dimension,

> *in a floor, roof, or other walking/working surface.", "Each employee on walking/working surfaces shall be protected from falling through holes (including skylights) more than 6 feet (1.8 m) above lower levels, by personal fall arrest systems, covers, or guardrail systems erected around such holes."*

However, unlike the safety regulation containing explicit instructions, safety regulations related to scaffolds provides highly general instructions about how to design and plan scaffolds. In practice, scaffolds are often planned based on intuitive understanding about the construction site conditions relying on experience and knowledge of individual engineers. Below shows an example of existing safety requirements for scaffolding in 1910.29(a)(1).

> *"Scaffolds shall be furnished and erected in accordance with this standard for persons engaged in work that cannot be done safely from the ground or from solid construction."*

As such, implicit knowledge and practices of scaffolding placement need to be investigated to identify the process of planning scaffolds which do not explicitly exist in written form. The placement process will eventually enable the automation or semi-automation of scaffolding planning and following safety analysis.

2. ***Step 2: Establish scaffolding placement process***

   Based on the investigation into existing practices and regulations, scaffolding placement process can be established. The placement process in human language provides step-by-step instructions on how a practitioner analyzes construction site conditions and makes decisions related to scaffolding placement.

3. ***Step 3: Automated building model interpretation***

   The established scaffolding placement algorithms are developed and implemented in this step. The placement process in human language is converted into computational algorithms that implement the process in BIM. The algorithms receive user-input and conduct tasks of analyzing the spatial- temporal conditions presented in digital building models. Project information can be found from BIM, construction schedule, and other documents developed for construction planning.

4. ***Step 4: Scaffolding object insertion***

   As a result of implementing scaffolding placement algorithms in BIM, scaffolding objects can be created and inserted into BIM and 4D BIM. Each scaffolding object contains necessary information used as the input for further safety analysis and optimization tasks. The breadth of information in a scaffolding object can be identified during earlier stages (step 1 and step 2).

5.4.2 Details to the development of Scaffolding Placement Engine

5.4.2.1 Interview round 1: Identification of overall scaffolding planning process

This section present works related to step 1 and step 2 in the proposed framework. As discussed earlier, due to lack of explicit rules, not only regulations but also implicit knowledge of industry professionals needed to be organized into a scaffolding placement process. This task was conducted mainly by literature review and in-depth interviews with construction professionals. The results were formulated into a sequence of actions to analyze construction site conditions and plan scaffolds.

Two general contractors, two subcontractors, and three scaffolding subcontractors participated in the interviews. In this research, the type of subcontractors was limited to masonry construction subcontractors that use scaffolds extensively. Three rounds of interviews were conducted. In the first round, interviewees were asked open-ended questions about how scaffolds are planned and how important construction site conditions are analyzed while planning scaffolds. Open-ended questions included:

- Central question: How are scaffolds planned in practice?

- How do you determine if a scaffolding is required?
- Why is the need for scaffolding identified in the planning stage?
  (e.g. quantity takeoff, safety analysis)
- Who identifies the needs for scaffolding?
  (e.g. General contractors, subcontractors)
- When are the needs for scaffolding identified?
  (e.g. design, construction planning, construction stage)
- How do you acquire information to identify needed scaffolding?
  (e.g. site visit, drawing, schedule, verbal description)
- How are the scaffolds designed and by whom?
- How potential safety hazards related to scaffolding are identified?
- How site conditions are analyzed for scaffolding installation, utilization, and demolition?

5.4.2.2 Interview round 2: Identification of major tasks in scaffolding planning

The results were qualitatively analyzed and organized into a form of a process chart. The process chart was reviewed by the interviewees in the second round and refined based on the feedbacks for the validity of the process. As a result, a detailed workflow for scaffolding design and planning was created (Figure 3). By analyzing the workflow, important tasks needed to plan scaffolds were identified. Major tasks are:

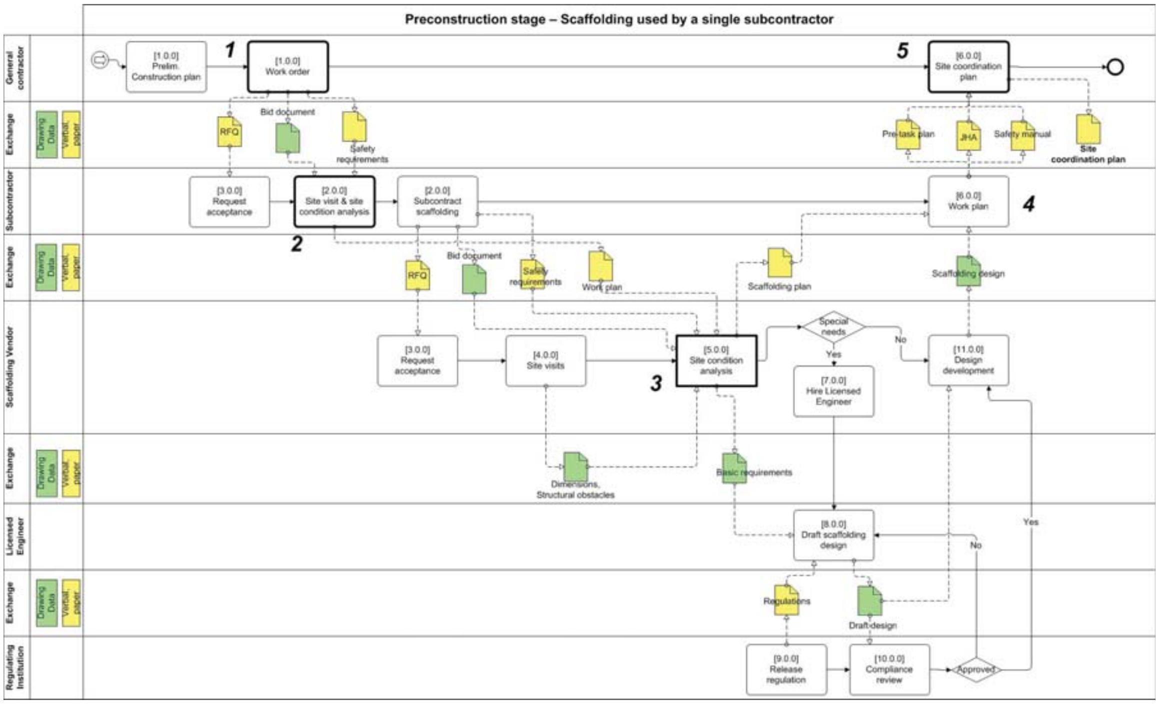


Figure 3: Identified scaffolding design and planning workflow

1. ***Work order by general contractor***

   In the construction planning stage, work packages are identified by the general contractor and request for quote (RFQ) is sent to subcontractors along with project information, such as bid documents and general contractors safety requirements.

2. ***Site condition analysis and work planning by subcontractor***

   Upon acceptance of the request, subcontractors analyze construction site conditions by conducting site visits and reviewing bid drawings. In this stage, the subcontractors create work plans to complete the work packages. If the need for scaffolding is identified, RFQ is sent to scaffolding subcontractors. Project information from the general contractor and the subcontractor's work plans are provided to the scaffolding subcontractor.

3. ***Site condition analysis and work planning by scaffolding subcontractor***

   Upon acceptance of the RFQ, the scaffolding subcontractor conducts site condition analysis by site visits or documents from the general contractor and the work plan of the subcontractor are utilized. The scaffolding subcontractor establishes detailed plan to supply scaffolding to subcontractors. The scaffolding plan needs to ensure that scaffolding is installed when it is need by the masonry crews.

4. ***Updated subcontractor work plan***

   The work plan created by the scaffolding subcontractor is combined with the work plan of the subcontractor using the scaffolding.

5. ***Site coordination planning by general contractor***

   Overall construction site coordination planning is conducted by the general contractor based on the work plans submitted by multiple subcontractors.

5.4.2.3 Interview round 3: Details about major activities of planning scaffolding

In the third round of interview, additional in-depth interviews were conducted to identify details about how the practitioners conduct the major tasks related to planning scaffolds.

- ***Work package recognition and rough work planning by general contractors***

  Even with the availability of 3D visualization in BIM, the general contractors participated in the interviews tend to describe work packages using simplified 2D representations, such as work areas and directions. Figure 4 shows a realistic masonry wall construction plan that comprise three work packages expressed by work directions. While the general contractors recognized that scaffolds were needed to construct the masonry walls, the masonry subcontractor was in charge of developing detailed work plans incorporating scaffolds. For the work packages, instructions provided to the masonry subcontractors were limited to work directions and approximated durations.

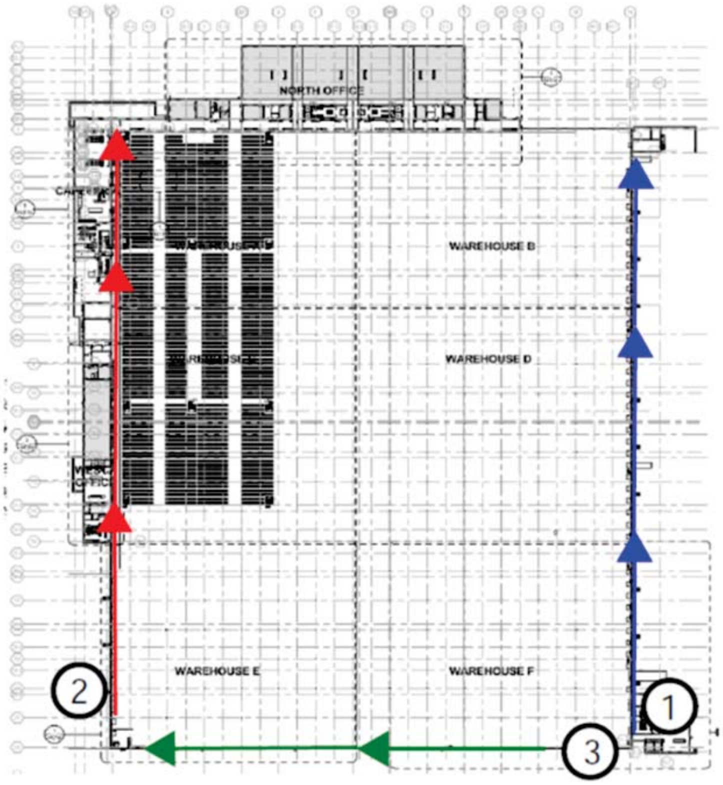


Figure 4: A general contractors masonry wall paths in a real construction project

- ***Detailed work planning by subcontractors***

  Based on the project information and work plans provided by the general contractors, subcontractors (masonry subcontractors) develop detailed work plans. Even though needed scaffolds could be identified by the general contractors, subcontractors often establish work plans including detailed scaffolding utilization plans. Compared to general contractors' site condition analysis, the subcontractors tend to analyze construction site conditions more comprehensively and predict potential safety and productivity issues.

During the interviews, masonry subcontractors were asked to plan scaffolding for masonry wall construction based on a given BIM model. When the subcontractors were planning scaffolding for the given project, the steps taken to analyze geometric conditions and plan scaffolds were recorded and organized.

1. **Identify masonry work faces**

   The masonry subcontractors first recognized the building components to be constructed. Figure 5 illustrates a masonry wall work package. This work package is composed of two walls that need masonry exterior finishing. The work face for this work package is the integration of the faces of Wall 1 and Wall 2. Even though this can be expressed by multiple wall components in BIM, the construction workers in real world perceive this as one work package that can be constructed without discontinuation. Figure 6 shows a larger work package that is composed of four wall components.

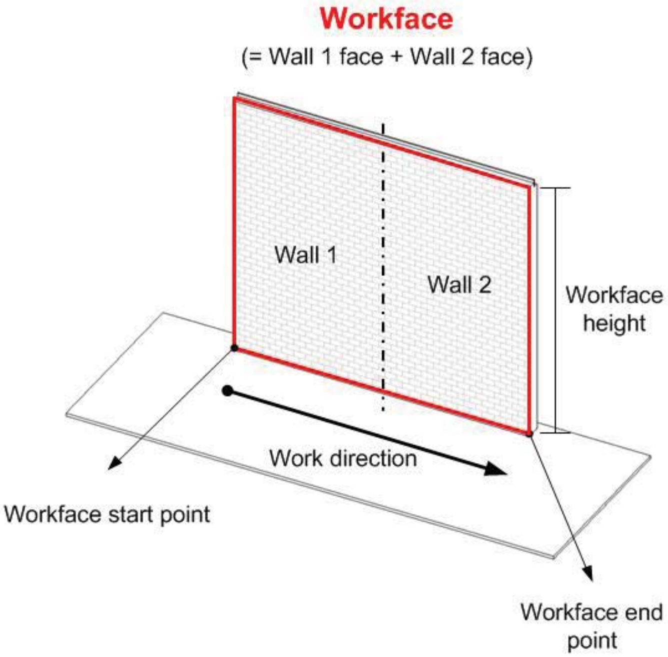


Figure 5: Geometric features recognized to plan scaffolding for a short masonry wall

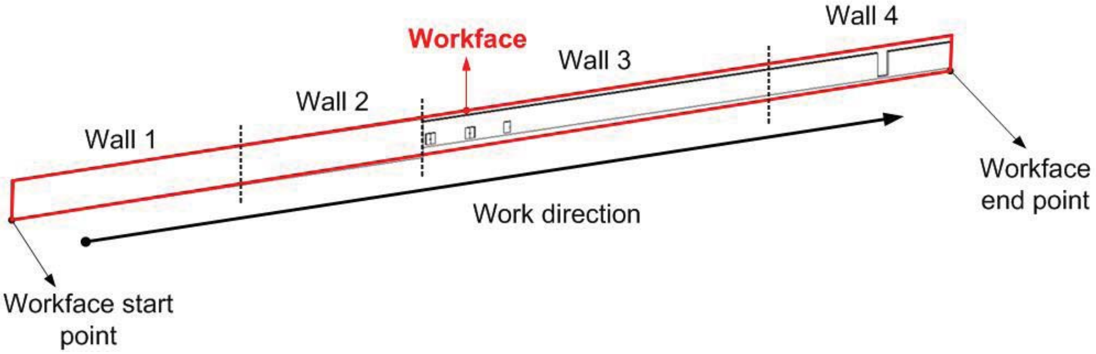


Figure 6: Geometric features recognized to plan scaffolding for a large masonry wall package

2. **Identify work scope and directions**

   Then, the masonry subcontractors identify the scope of the work package and decide the work pattern they will implement to complete the work.

Work patterns can be decided by the general contractors or the subcontractors. In Figure 5 and Figure 6, the work directions are shown by arrows.

3. **Identify the height of the workface**

   The masonry subcontractor identified heights of work locations along the masonry wall. The heights of work locations determine if scaffolding is required. If the height changes along the work face, different sizes of scaffolds may be installed to support the activities of the subcontractors.

4. **Establish subcontractors work plan**

   After the geometric condition is analyzed, the subcontractors establish the plans to construct the subcontracted work packages.

   (a) The number of work crews is decided to meet the deadline set by the general contractor. Historical productivity data is commonly used to calculate the required work force.

   (b) The work package is subdivided into daily or weekly work packages

   (c) Scaffolding required to support daily or weekly work is identified. Even though scaffolding types can be determined in this step, it is out of the scope of this research. Figure 7 and Figure 8 visualize the simplified scaffolding representations. As well as identifying the spaces and rough geometry of a scaffold, the expected progress of masonry activity can be associated as shown in Figure 8.

   (d) Daily or weekly construction site conditions are analyzed to identify safety hazards that can occur related to scaffolding. Specific tasks conducted by the subcontractors include:

      i. Identify other crews working under or over the scaffolding used by the masonry crews

ii. Identify adjacent loading and lifting activities that can cause falling objects to scaffolding and masonry crews

iii. Evaluate accesses to scaffolds for workers and material delivery

iv. Identify areas for material storage and evaluate its spatial relationship with scaffolds

v. Identify power lines adjacent to the scaffolds that can cause electrocution

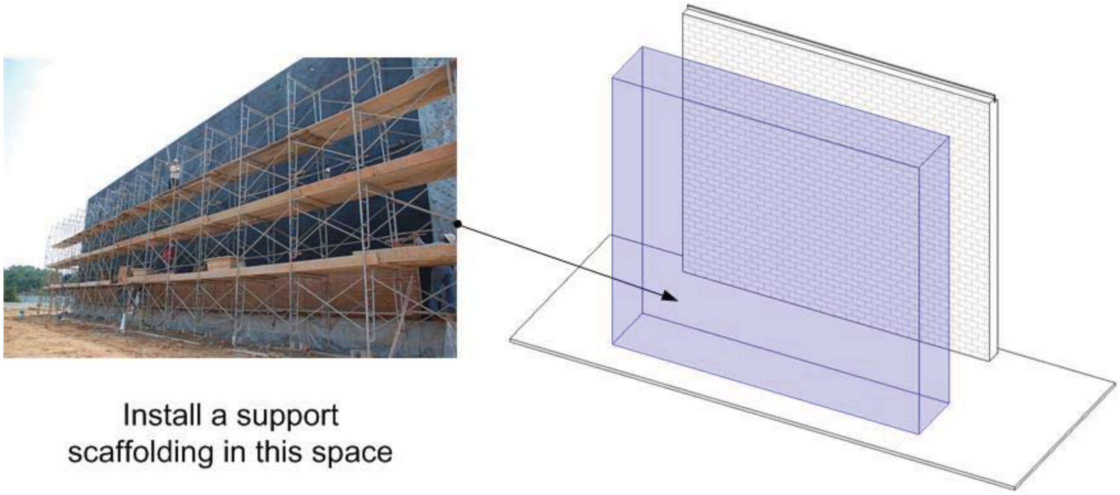


Figure 7: Simplified representation of a scaffolding object

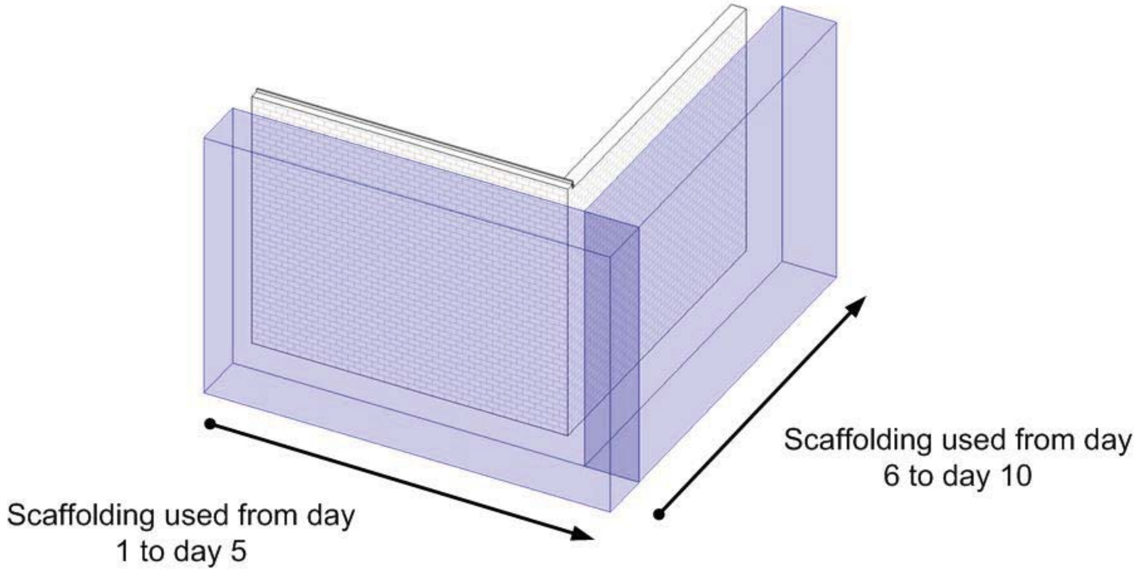


Figure 8: Scaffolding objects associated with schedule information

(e) Provide the work plan to the scaffolding subcontractors

The work plans established by the masonry subcontractors are provided to the scaffolding subcontractors to develop detailed scaffolding designs.

- ***Detailed scaffolding design creation by scaffolding subcontractors***

  After basic shapes and related schedule dates were determined by the masonry subcontractors, scaffolding subcontractors refine the rough scaffolding plan into detailed scaffolding designs that can be used as benchmark for field installation (Figure 9). The developed designs need to comply with safety regulations. In addition to the rough geometric properties already obtained (scaffolding height, start point, end point, etc.), additional information added to refine the scaffolding space. The information include ground condition, work face-to-scaffolding distance, width of the scaffolding space, and connections between walls and scaffolding.

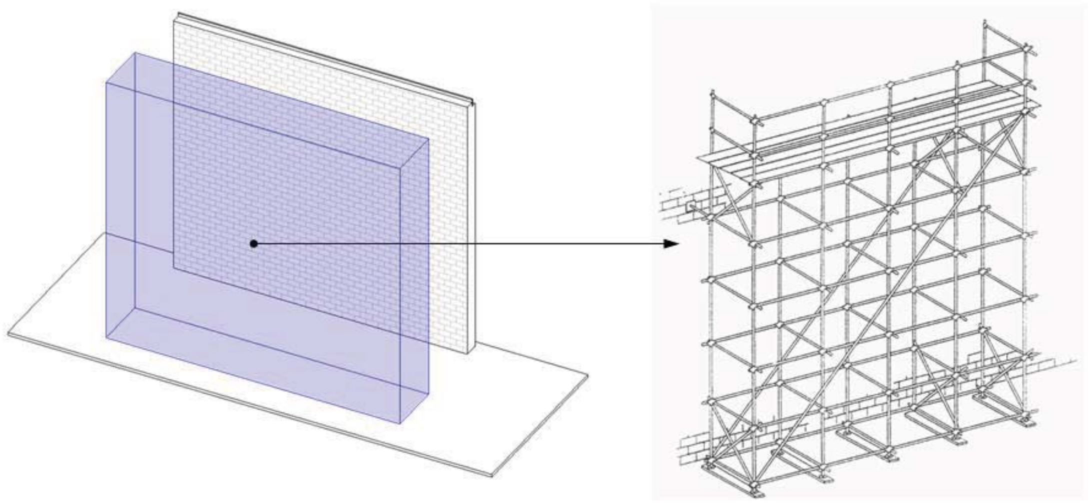


Figure 9: Design details created in a scaffolding space

5.4.2.4 Summary of scaffolding placement process and its implementation in BIM

As a result of conducting three rounds of interviews and analyzing the outcomes, scaffolding placement process and information requirement for scaffolding were established. The important activities of planning scaffolds were organized as shown in Figure 10.

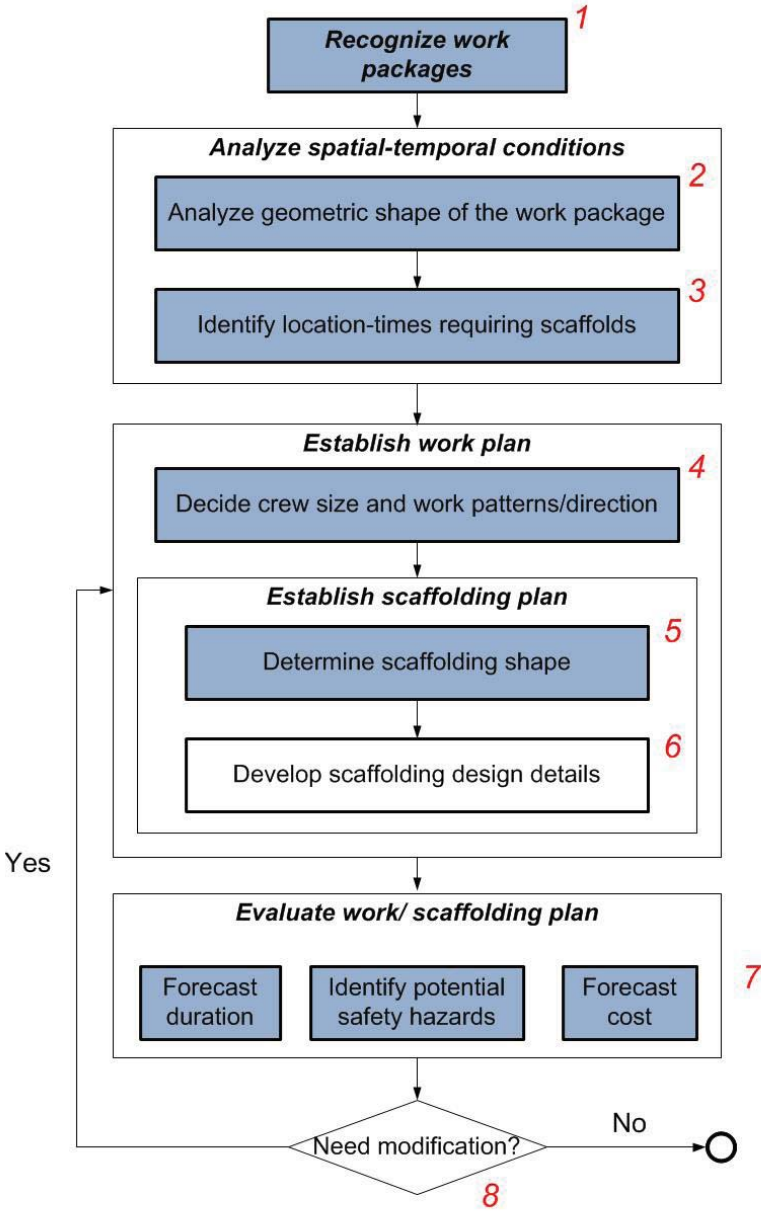


Figure 10: Scaffolding placement process

1. **Recognize work packages**

   4D BIM is established by creating virtual links between building objects and schedule activities. By establishing 4D BIM, recognition of work packages can be conducted in BIM. Thus, the proposed scaffolding placement approach requires 4D BIM readily created by the users.

2. **Analyze geometric shapes of work packages**

   Then, the geometric properties of scaffolding are analyzed. Important features, such as end points and heights of the work faces, are identified.

3. **Identify location and times requiring scaffolds**

   After analyzing geometric conditions of the work packages, the locations and times requiring scaffolds are identified.

4. **Decide crew sizes and work patterns/directions**

   Since installation and utilization of scaffolds are directly impacted by the characteristics of work plans, work plans need to be established before basic shapes of scaffolds are determined. In this step, several decisions, such as crew size, work directions, and work pattern, are made.

5. **Determine scaffolding shapes**

   After establishing the work plan, shapes of scaffolds are determined and the location and time of scaffolding installation and utilization are decided. In this step, scaffolding objects are inserted into 4D BIM.

6. **Develop scaffolding design details**

   Detailed scaffolding designs can be created in the scaffolding boundary. However, this is out of the scope of this research.

7. **Evaluate work/scaffolding plans** (Chapter 6)

   The 4D BIM incorporating scaffolding objects can provide more realistic visualization of construction progresses. Potential safety hazards in the plan can be identified. In addition to safety, other important goals of construction (such as cost and duration) can be evaluated. In this research, objective 2 accomplishes this task automatically.

8. **Refine work/scaffolding plans** (Chapter 7)

   Based on the evaluation in terms of safety and other goals, scaffolding plans can be refined into safer and more productive plan. Objective 3 of this research accomplishes this task.

5.4.2.5 Scaffolding information requirements

Required properties of a scaffolding instance have been organized into three categories. These properties are needed for visualization and safety analysis of scaffolding in BIM.

1. **Geometric properties**

   (a) geometric properties are used to visualize the shape of a scaffolding instance in BIM.

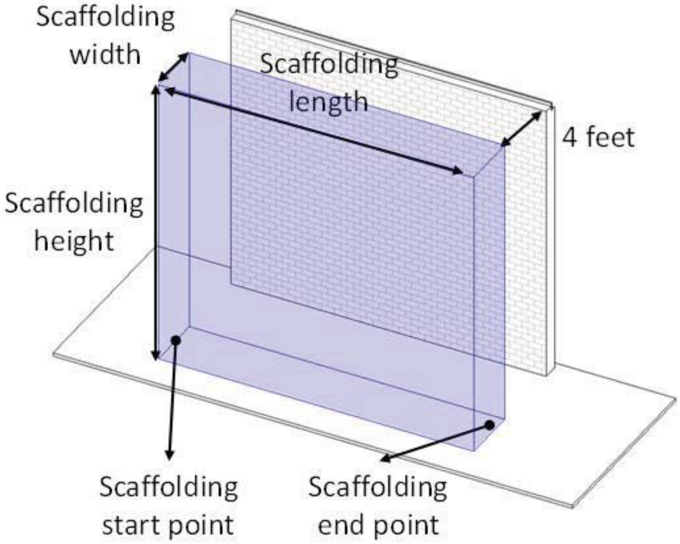


Figure 11: Shape of a scaffolding space

    (b) Scaffolding space (Figure 11): A space occupied by a scaffolding can represent the scaffolding instance required for the purpose of this research. A bounding box can be created based on start and end points, width and height of a scaffolding. The distance between the bounding box and a wall can be decided based on the regulations and characteristics of activities using the scaffolding. This rough representation of scaffolding shape can potentially include detailed scaffolding design even though it is not in the scope of current research.

2. **Scheduling properties**

    (a) Visualization and safety analysis of scaffolding require both spatial and temporal conditions of a construction site properly represented in 4D BIM. Thus, a scaffolding instance needs to contain following information.

    (b) Task information: A scaffolding instance has to be linked to a schedule task that utilizes the scaffolding. Start date and finish date of the task can be used to determine when the scaffolding instance will appear and disappear from both visualization and analysis.

    (c) Crew information: Information about work crews using the scaffolding need to be available too. A work direction to complete a task may need to be specified since it determines the spatial flow of the work crew using the scaffolding. Depending on the spatial flow, daily workspace in the scaffolding instance can change. The number of crews also need to be specified since daily work productivity and the size of workspace can change depending on the crew size.

3. **Properties for safety analysis**

    (a) In addition to geometric and schedule information, it was found that additional information is needed for safety analysis related to scaffolding. Scaffolding instances need to contain properties that are needed to conduct safety hazard analysis.

    (b) Limited access zone: In case of masonry wall construction, limited access zones are defined prior to the construction. No other employees except those actively participating in the wall construction are permitted to enter the zone.

    (c) Workspace (Figure 27): The space occupied by a work crew needs to be included too. If the scaffolding size is large, a work crew may use only a small portion of the scaffolding. In order to conduct daily construction site safety condition analysis, workspaces of each day need to be identified. In Figure 27, a workspace of a crew has been visualized as part of the scaffolding space.

    (d) Ground condition: Ground condition may also need to be incorporated since it impacts how the scaffolding can be installed.

    (e) Adjacent power lines: Power lines adjacent to scaffolding need to be detected so that the placement plan for the scaffolding can be changed or other protective action can be taken.

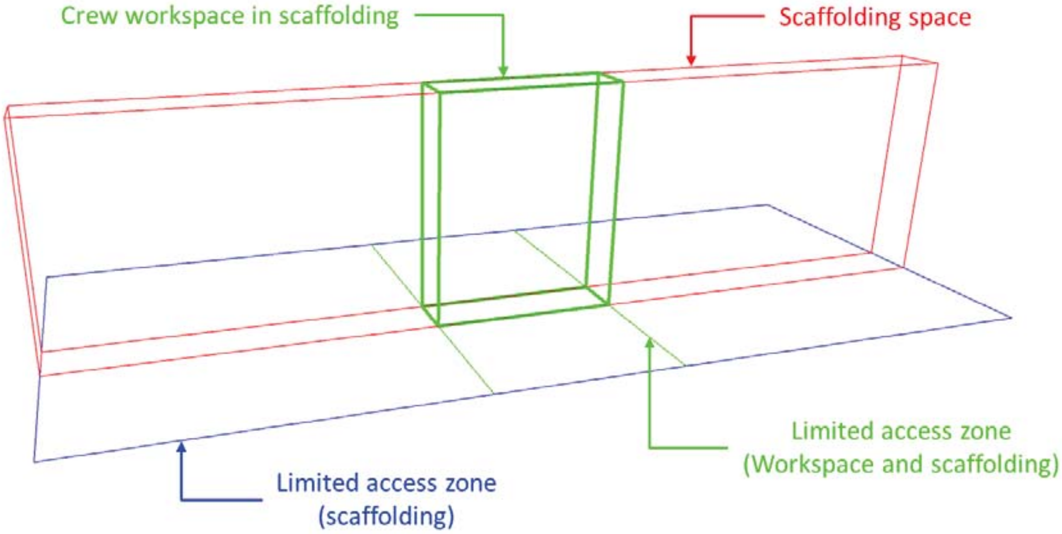


Figure 12: Analytical view of scaffolding and workspace

5.4.2.6 Translation of scaffolding placement process into computer-readable algorithms

As a result of three rounds of interviews, scaffolding placement process and scaffolding information requirement have been established. In this chapter, the scaffolding placement process is translated into algorithms that can be implemented in BIM.

The algorithms utilize information in 4D BIM and user input related to scaffolding placement in order to create scaffolding objects. By implementing the algorithms, scaffolding objects are expected to be created that can be used for automated safety checking and optimization.

1. **Recognize work packages**

   Recognition of work packages is conducted by using 4D BIMs virtual links between building components and tasks in construction schedules. Building components (e.g. walls) composing a work package need to be linked to a task (e.g. masonry wall construction) in a construction schedule before the scaffolding placement algorithms are implemented. In addition to basic information of 4D BIM, work directions have to be specified by users as shown in Figure 13. The work direction represents the planned spatial flow of a work crew which is essential in simulating daily construction site condition in BIM.

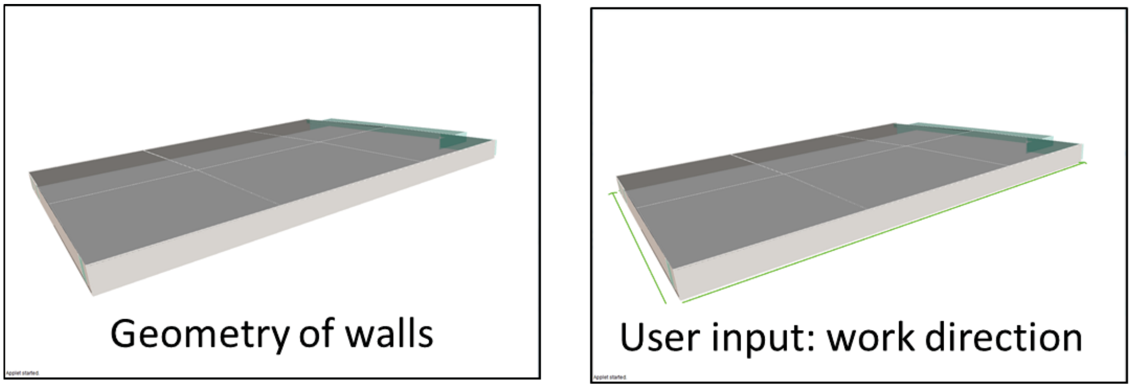


Figure 13: Masonry walls and user-defined work directions

2. **Analyze geometric shapes of work packages**

   Based on properly constructed 4D BIM and user input, geometric conditions of the work packages are automatically analyzed in this step. Both building geometry and work directions are used as the input for computer-driven geometric condition analysis. To account for heights work faces that may change, the heights need be checked along the work directions.

   In order to enable automated checking, inspection points are created along the paths of work directions. While the inspection points were created every 3 feet in Figure 14, this can be adjusted by users based on the geometric characteristics of the project. The inspection points are 4 feet offset of the wall faces to account for an existing safety regulation. The inspection points are used then to identify the heights of the work faces along the path. To identify bottom and top of the wall surface, plane-face intersection analysis was conducted for each inspection point.

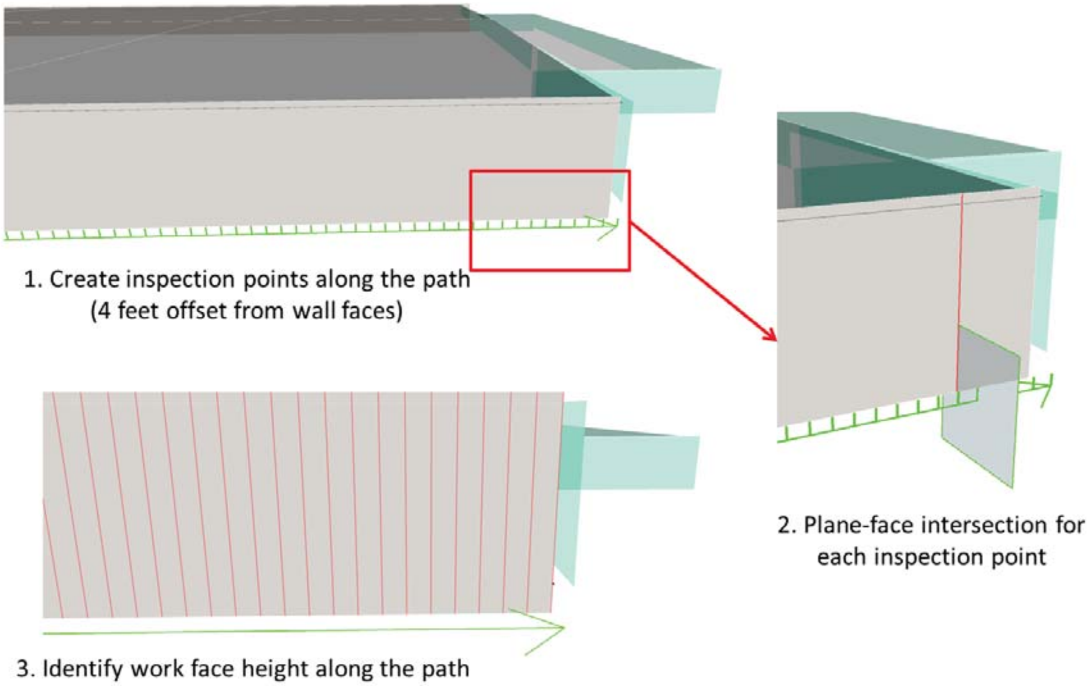


Figure 14: Plane-face intersection for each inspection point

3. **Identify location-times requiring scaffolds**

   By inspecting all the inspection points along the work path, locations in need of scaffolding can be identified. This can be done by comparing the work face height at each point with a predefined height, such as 1 meter for masonry construction, which needs scaffolding.

4. **Decide crew sizes and work patterns/directions**

   After analyzing the geometric conditions in a work package, additional information on work crews and work patterns are required. The number of work crews participating in the construction of the work package impacts daily work productivity and thus how much workspace is occupied each day. A pattern for scaffolding installation also needs to be determined. A scaffold can be installed along the entire work package or scaffolding installation can take place once a week, for example.

5. **Determine scaffolding shapes**

   As a result, scaffolding objects are created in BIM. Scaffolding objects are visualized as bounding boxes. Task details are automatically generated to support daily construction site condition representation and visualization.

5.5 Implementation of scaffolding placement algorithms

After developing the algorithms, the Scaffolding Placement Engine was in a 4D BIM of a real construction project. A single-story commercial building construction project used scaffolds for brick masonry exterior wall construction. 4D BIM, productivity of masonry wall construction, and work directions of masonry wall construction were used as the input. After implementing the Scaffolding Placement Engine in the case study project, the results were reviewed by masonry subcontractors and scaffolding subcontractors to validate if the automated algorithms generate rational results of scaffolding placement.

Figure 15 and Figure 16 illustrate the results of plane-face intersection for simple and complex work faces, respectively. For the simple walls, the height of the work face can be acquired by evaluating one inspection point. However, to plan scaffolds for the work face of geometrically complex shape, all the inspection points need to be evaluated.

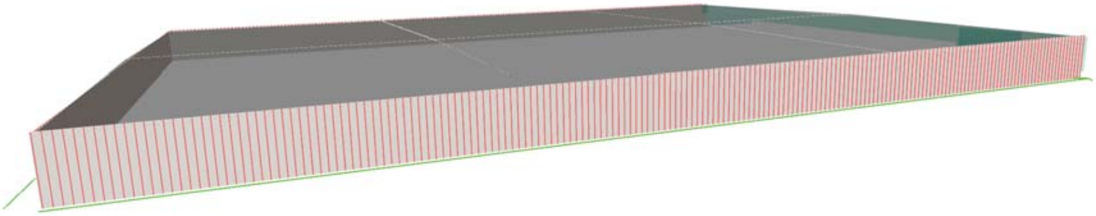


Figure 15: Plane-face intersections of rectangular walls

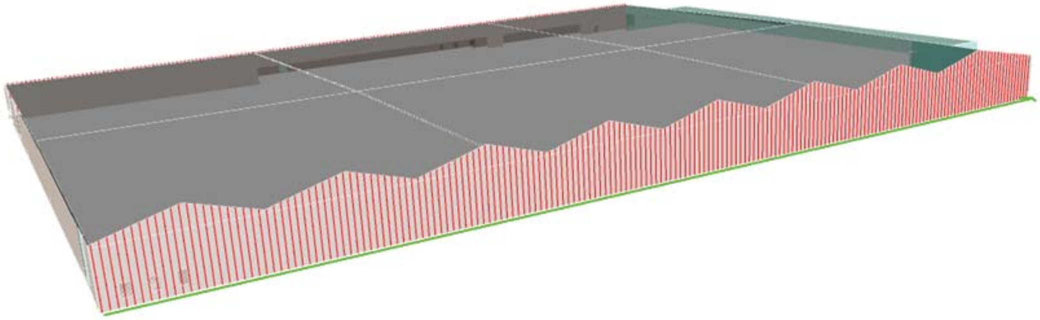


Figure 16: Plane-face intersections of walls with varying heights

After evaluating the heights of work faces, scaffolding objects and workspace objects are created.Figure 26 shows daily scaffolding spaces and workspaces placed along the masonry wall. The size of daily workspace is equivalent to the daily output of the crew. Therefore, if the crew size increases, the daily workspace size increases linearly. This represents the planned progress of the masonry subcontractor. Based on the masonry subcontractors plan, scaffolding plan is created. In this case (Figure 26), scaffolding is installed every five days. Thus, one scaffolding space encompasses five daily workspaces.

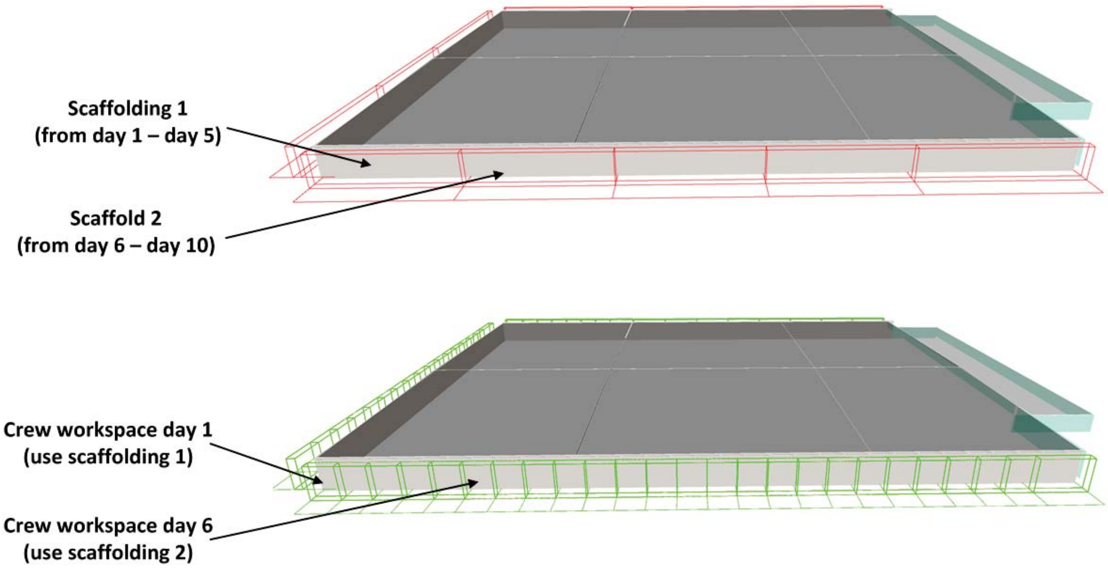


Figure 17: Scaffolding and workspace instances created along the path

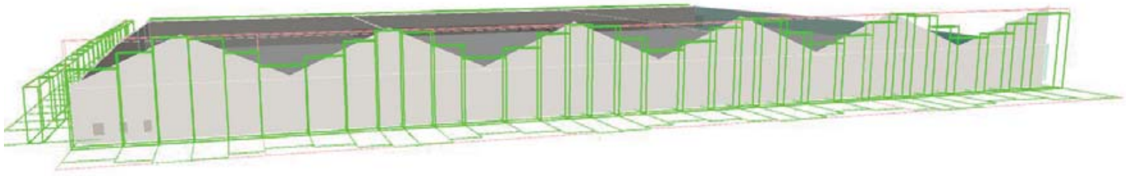


Figure 18: Daily workspaces created along the work direction

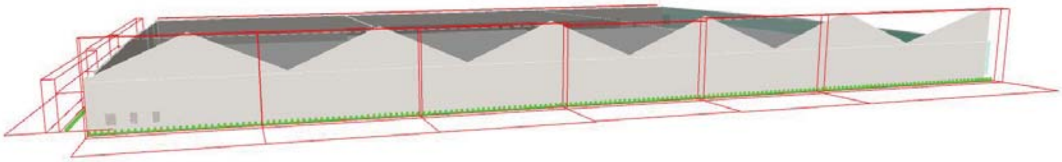


Figure 19: Scaffolding space created based on maximum work face heights

Shapes of daily workspaces change according to the geometric shapes of the wall faces. Scaffolding spaces were created for every five days. The height of a scaffolding space was set as the greatest height of the workspaces.

Finally, all the scaffolding objects, workspaces, and analytical geometry (limited access zones and work directions) have been incorporated into 4D BIM. Figure 20 and Figure 21 illustrate 4D simulation of day three and five, respectively. Since scaffolding installation takes place every five workdays, installation of new scaffolding is planned on day five (Figure 21).

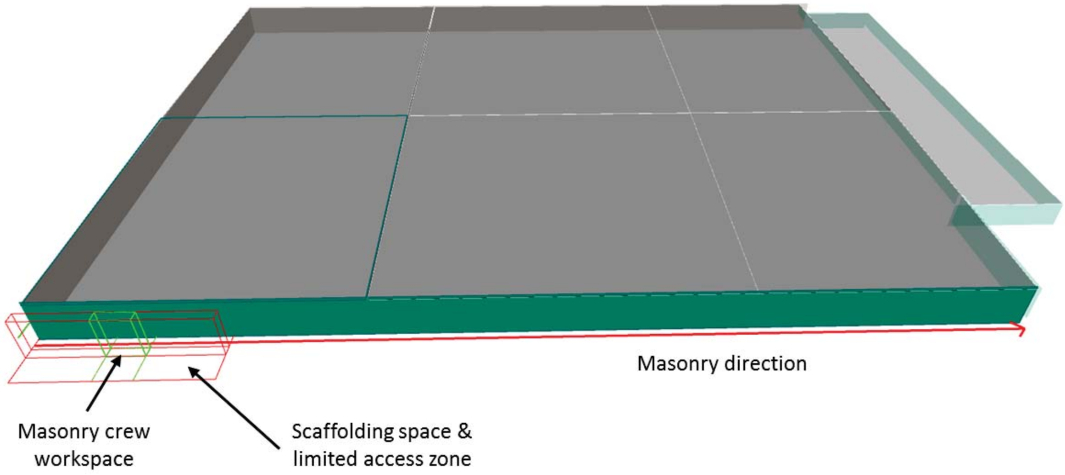


Figure 20: Scaffolding objects and workspaces incorporated into day 3 of 4D BIM

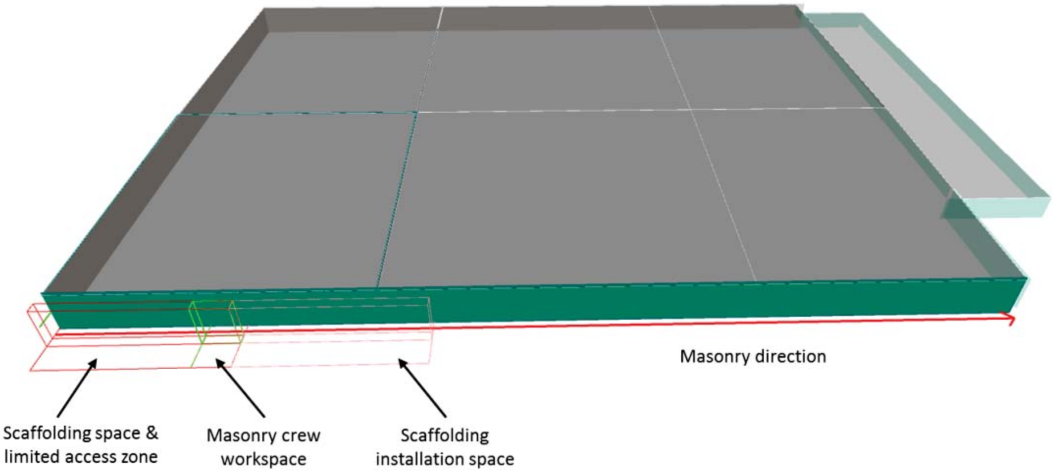


Figure 21: Scaffolding objects and workspaces incorporated into day 5 of 4D BIM

5.6 *Conclusions and discussion*

Scaffolding placement process was established by based on in-depth interviews with industry practitioners who have participated in planning of scaffolds. The identified placement process was then converted into computational algorithms that can implemented in digital building models. The developed Scaffolding Placement Engine was tested in a real construction project model and the results were reviewed by the interviewees. The results indicate that the developed system can create scaffolding objects in BIM without excessive reliance manual efforts. When directions of work crews using the scaffolds were provided, the algorithms could create simplified scaffolding objects, workspaces occupied by work crews on each day. In addition to the geometric shapes, the algorithms created properties important for construction and safety analysis, such as limited access zones, scheduled start and finish dates, the name of the crew using the scaffold, etc. In the following chapter, an automated safety hazard checking approach will be introduced that uses the accomplishment of this chapter. There are limitations of the proposed approach that need to be solved. Theses are: (1) For different types of tasks other than masonry wall construction, scaffolding placement process may need to be identified. As discussed, planning and analyzing temporary structures rely heavily on implicit knowledge and reasoning capabilities of engineers instead of following explicit rules. Therefore, there could be many types of processes of planning scaffolding. However, this task may require intensive investigation into patterns of work tasks. (2) The scaffolding placement algorithms require work directions as an essential user input for automated analysis. In order to achieve a greater level of automation, possible work directions can be automatically derived from the building geometry. However, in this research, work directions planned by general contractors and subcontractors were simply used and focused on the creation of scaffolding and workspace objects.

CHAPTER VI

AUTOMATED CHECKING OF SCAFFOLDING-RELATED SAFETY HAZARDS IN BIM

This chapter introduces an automated safety hazard analysis to identify potential safety hazards related to scaffolding. Safety Simulation Engine integrates safety knowledge and scaffolding objects into a BIM-based site condition simulation. By integrating spatial-temporal flows of construction crews and scaffolds, current construction planning using BIM can be extended from plain visualization toward automated knowledge-based analysis of construction safety that can alert construction planners of potential safety hazards and sources of productivity losses. A case study using a real world construction project information demonstrates the capabilities and effectiveness of the developed Safety Simulation Engine.

6.1 Introduction

Despite various efforts, still construction is a hazardous industry that can potentially expose construction workers to fatal hazards. Falls from elevation, struck by objects, electrocutions, and caught-in/between were identified as leading causes prevention of which could save more than 400 lives of US workers. These potential safety issues need to be addressed in early design and construction planning stages.

However, in current construction industry, safety planning processes are often separated from the design and construction planning. Despite the significant impacts on the project, construction safety planning usually takes place after important parts of a construction plan are already established. In order words, safety communications do not occur among project participants early in a way that contributes to the creation of safe construction strategies. Instead, the responsibility of construction safety planning is often limited to identifying potential safety issues from the existing construction plans. Also, the current safety planning relies on labor-intensive and time-consuming manual efforts, which is often error-prone and inconsistent.

There has been advances in BIM and sensing technologies to address safety problems in the construction industry. Recent research studies pointed out the need for automated planning of construction safety to overcome the deficiencies of manual efforts. One of the approaches is the rule-based safety planning system [44]. This system automatically identifies potential fall hazards and suggests preventive measures. Even though existing BIM-safety integration approaches attempt to address safety issues automatically by analyzing project information in BIM and schedule, many of critical aspects of construction are deficient from those approaches. The aspects can include:

- **Temporary structures**: Temporary structures, such as scaffolds, are frequently used by work crews along the spatial flows impacting the entire safety and productivity. These temporary structures are rarely planned or analyzed for safety.
- **Spatial flows of work crews**: The number of crews and their spatial movements within the construction jobsite is critical for safety. In practice, spatial flows of important crews are created
- Other movements: Within construction sites, there are various spatial flows (e.g. site or building entrances and material delivery) that can cause spatial conflicts.

While these are important construction planning components impacting the entire safety and productivity of the project, either industry practices or existing innovations fail to integrate these into BIM-based automation which can lead to improved safety.

This whitepaper proposes an innovative approach to BIM-safety that integrates the spatial-temporal dynamics created by movements in the construction site.

The original construction plan will be used as the input information for the safety checking system. A rule-based safety checking algorithms identify potentially unsafe conditions from the plan based on predefined safety rules. The rules are established based on the safety knowledge obtained from comprehensive interviews with construction and safety experts. As a result, the rule-based safety checking system will automatically identify safety hazards and visualize them to facilitate safety communications among construction participants.

6.2 Objective and scope

To overcome the technical limitations, this research proposes a new approach that integrates work sequences and temporary structures into the automated safety checking system using BIM. There are two tasks for the development of Safety Simulation Engine.

1. BIM-safety platform: Create a platform that incorporates work path plans of crews and their temporary structure utilization to simulate 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, the outcome of this research can be further integrated into automated scaffolding design generation approaches [21] 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.

6.3 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 proposed BIM-based safety analysis automation that includes the framework and technical details and algorithms.

6.3.1 Framework of BIM-based safety analysis automation

Figure 22 illustrates the framework of the automated safety hazard analysis proposed in this research. There are three major capabilities that are combining, analyzing, and sharing:

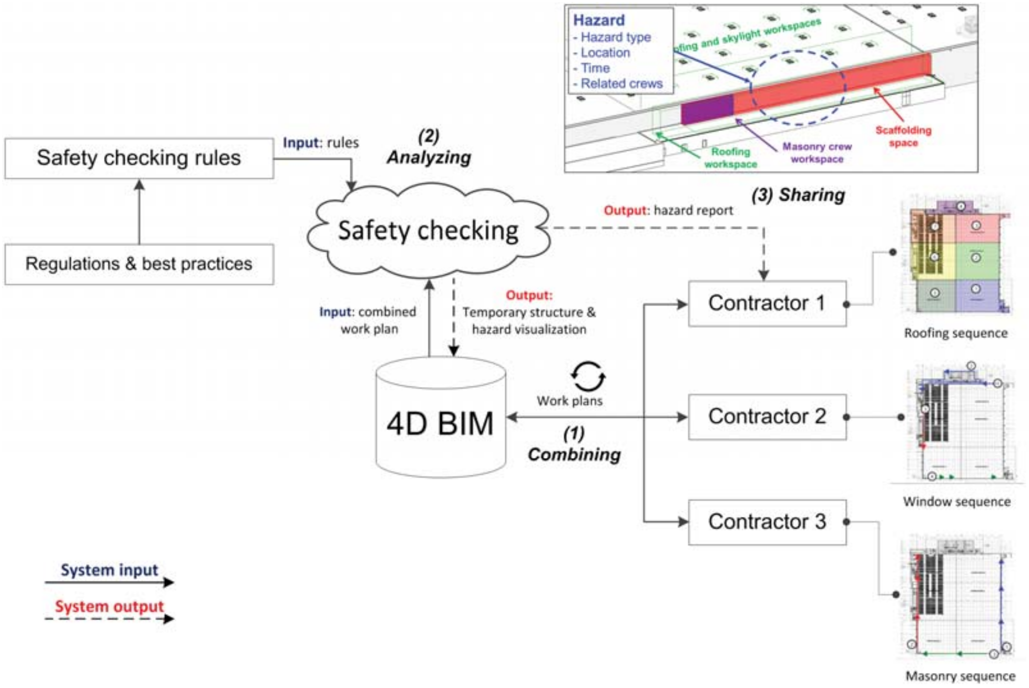


Figure 22: Framework for automated BIM-safety platform

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 of the proposed BIM-safety platform 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 as user-input.

2. **Analyzing**: The analyzing function creates activity details and simulates

construction site conditions. To analyze construction site safety realistically, daily work plans for all the major subcontractors need to be available. However, work plans of such details are rarely available due to the shortage of human resource for construction planning and complexity of projects. Thus, based on the user-input, the analyzing function automatically generates details of crews activities. By doing so, daily construction site conditions can be simulated and unsafe conditions can be 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 identifiable hazards. Upcoming scaffold installation, utilization/inspection/ demolition can be automatically identified and distributed as well.

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.

6.3.2 Technical details of BIM-safety platform

The technical details of the BIM-safety platform are presented in this section. Figure 23 illustrates the proposed system architecture of the platform. Autodesk Revit (BIM), Microsoft Project (schedule), and their Application Programming Interfaces (APIs) were used for the prototype development.

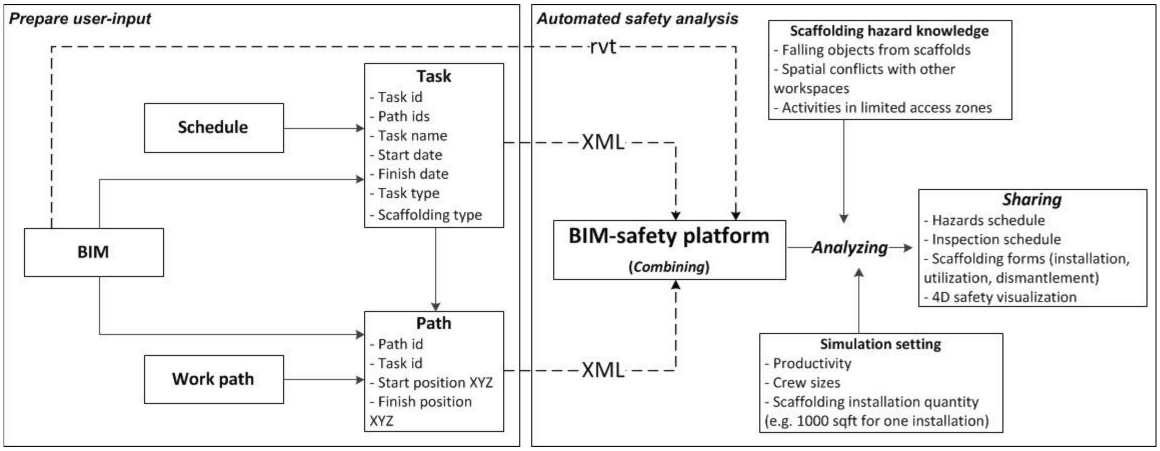
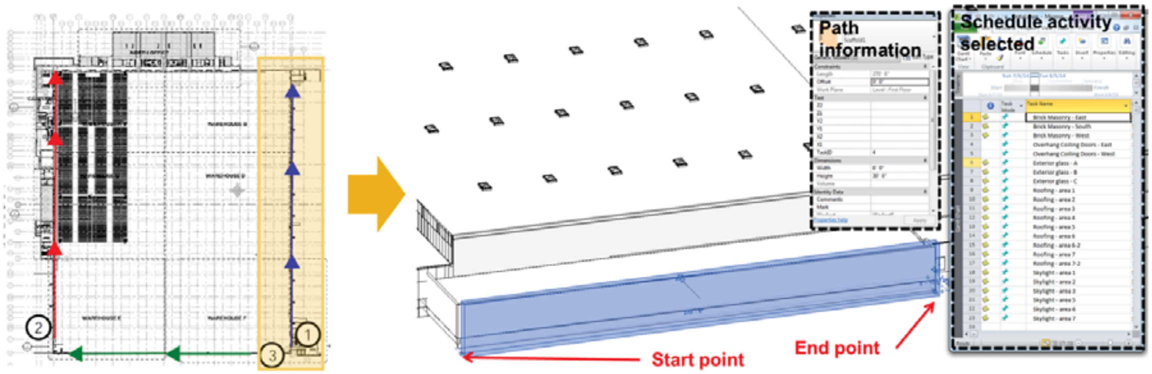


Figure 23: BIM-safety platform system architecture

6.3.2.1 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 Figure 24 (a). In this research, the users are prompted to insert the paths in 3D environment of BIM. Figure 24 (a) shows the masonry wall paths in a real construction plan. Figure 24 (b) shows a work path generated in our 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 Figure 23).

After preparing the user-input, XML files for tasks and paths are generated and combined using plug-ins we developed for this step. In addition to building model information, the task and path XML files are essential inputs for the automated safety simulation.



(a) 2D work path

(b) work path creation in BIM

Figure 24: BIM-safety platform system architecture

6.3.2.2 *Analyzing and sharing*

The proposed approach uses workspaces as the basic spatial elements for safety analysis. For activities not linked to any path plan, workspaces are created based on the zoning plans. For activities linked to work paths, daily crew workspaces and scaffolding spaces are generated along the paths. The workspaces and scaffolding spaces are then used for safety analysis. Further details are presented below.

1. **Workspace generation**

Creating workspaces as part of construction planning has been proposed by several research studies in the past. Methods have been developed to create workspaces based on building objects [2] or characteristics of tasks [24]. In our approach, workspaces are automatically created by taking advantage of zoning plans commonly existing as essential part of construction strategies. Since construction zones provide boundaries of work packages and sequences among them, the proposed BIM-safety platform uses the geometry of zones to create workspaces occupied by work crews. Figure 25 illustrates workspaces generated for different zones. The green box in Figure 25 (a) shows a workspace for foundation in Zone 1 and the green box in Figure 25 (b) presents a workspace for skylight installation in Zone 2. In addition to the zone boundaries, the workspace has been created below each skylight to account for the potential falling objects from above hazard (see Figure 25 (c)).

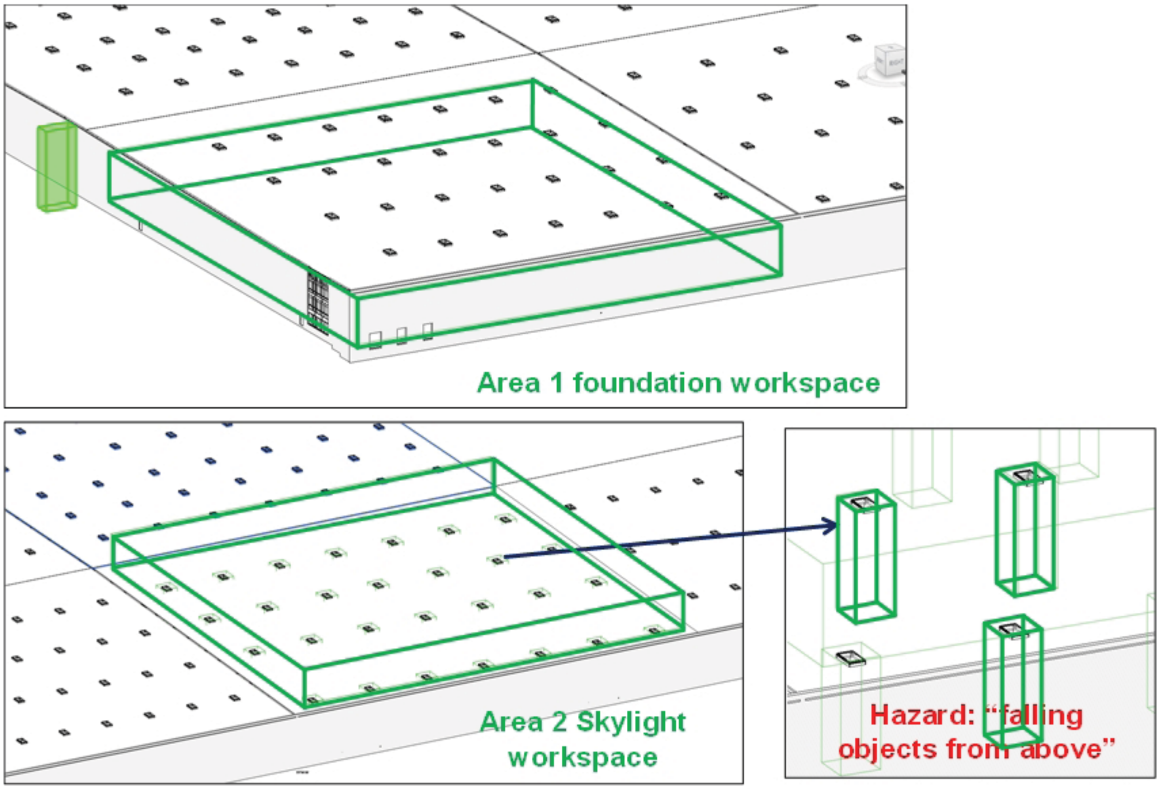


Figure 25: Workspace generation for activities

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 to day-to-day activities of crews. For example, the path in Figure 24 (a) presents the planned direction of the masonry crew along the wall. When the amount of brick masonry installation is large, this work package can be completed 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. Figure 26 shows activity details related to a brick masonry wall construction automatically generated by our system. Estimated crew productivity and the size of scaffolding installation were used to subdivide the entire space in front of the masonry walls. The work paths specified during the user-input preparation were used to determine the movement directions of the workspaces and scaffolding spaces during the simulation. As shown in Figure 27, crew workspaces, scaffolding spaces, and limited access zones on both sizes of scaffolding and workspaces can be created automatically. 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 scaffolding. Limited access zones are created according to a safety regulation. [1, 41] presents a research study on object splitting to support the creation of realistic 4D BIM.

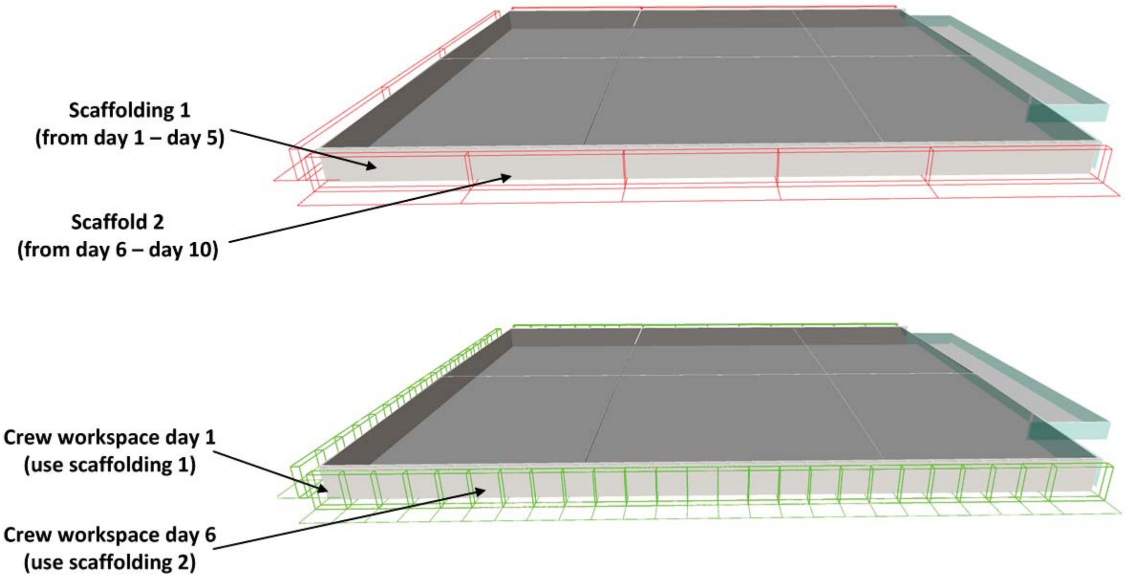


Figure 26: Automated detail generation based on input work sequence and assumptions

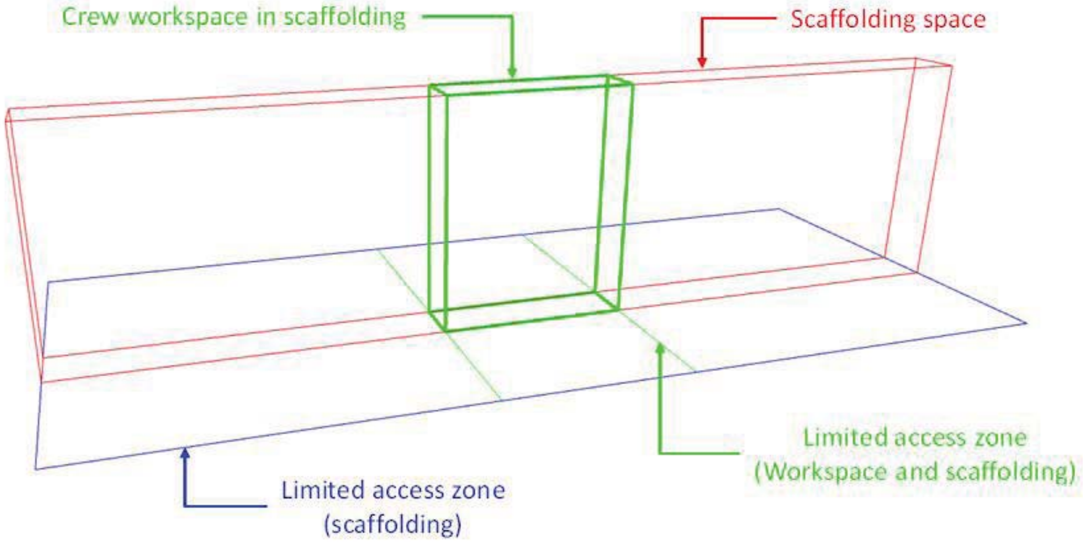


Figure 27: Scaffolding space, workspace, and limited access zones

Figure 28, Figure 29, Figure 30 illustrate an example of daily activity detail generation. In Figure 28, a building model is shown and a roof and a wall to be constructed are highlighted. The wall will be constructed following the planned work direction. As a result of applying the space generation algorithm, scaffolding and work crew spaces were generated for the wall construction, and a workspace for a roof construction was generated by extending the boundary of the roof (Figure 29). The spatial elements were integrated into the 4D BIM as shown in Figure 30. In this way, daily schedules of crews and scaffolding installation/utilization/dismantlement can be generated without excessive manual efforts. Figure 31 shows that workspaces and scaffolding spaces for each day can be generated automatically.

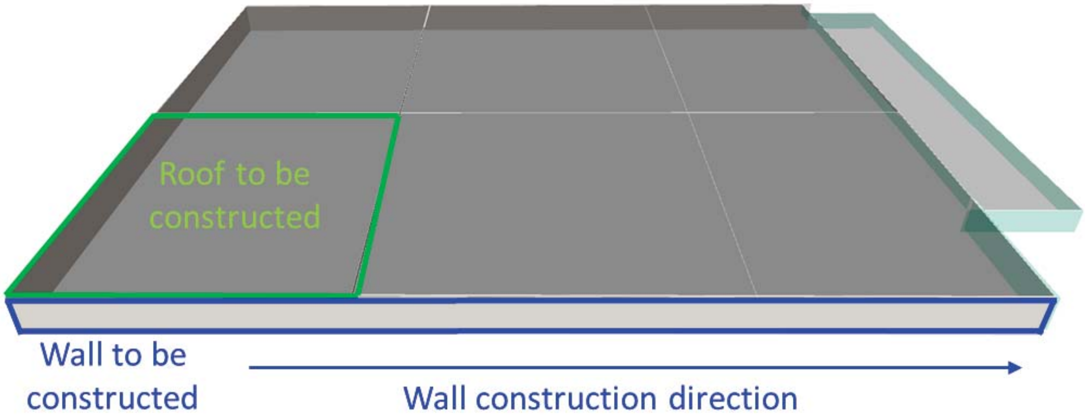


Figure 28: 4D BIM with on-going construction tasks highlighted

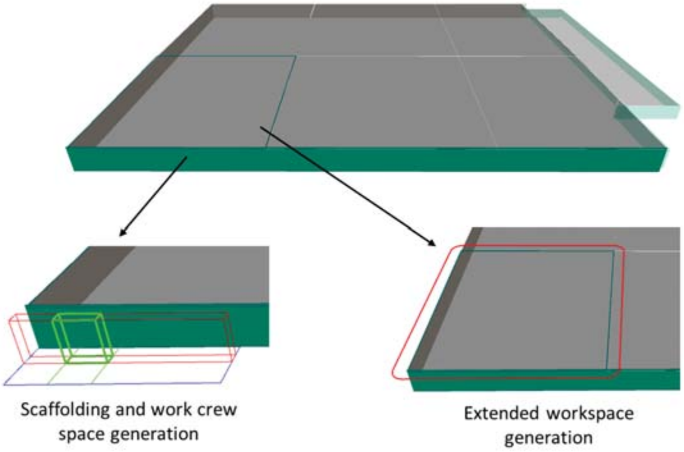


Figure 29: Workspace generation for the building model

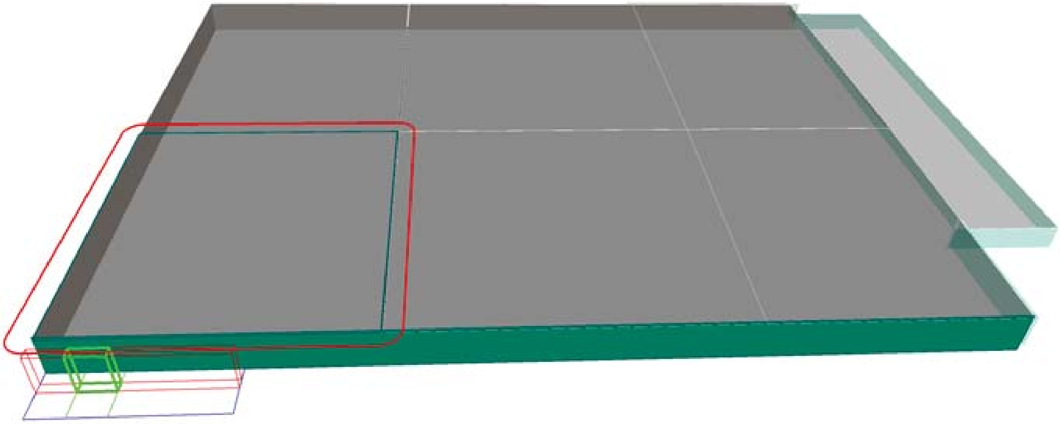


Figure 30: 4D BIM with spatial information integrated

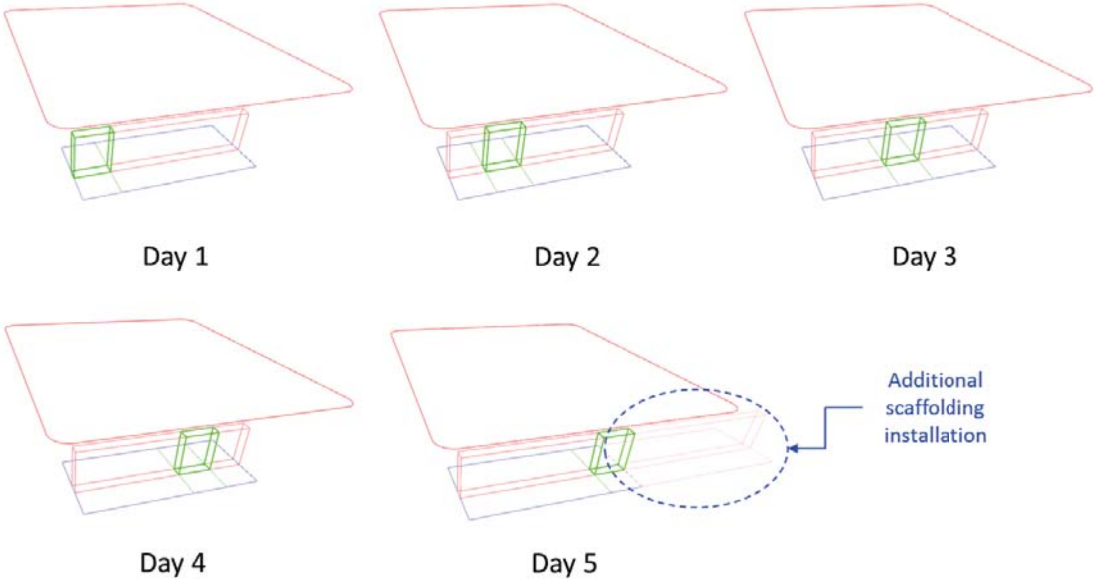


Figure 31: Daily workspace movement and scaffolding installation

3. **Safety simulation and hazard identification**

   After details including workspaces, scaffolds, and safety components (e.g. limited access zones) are created for each activity, construction site conditions of each day are simulated. This utilizes the scaffolding safety knowledge that explains what types of safety hazards can potentially occur in certain situations. The knowledgebase can be found from safety regulations or stricter industry practices of construction companies.

   As discussed in the introduction section, scaffolding can cause many types of safety hazards including falls from scaffolding, 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 2,000 deaths and the first leading cause of non-fatal injuries [12]. 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 general contractors, scaffolding subcontractors, and masonry subcontractors to define a list of conditions related to scaffolding that can cause struck-by safety hazards. As shown below, three types of conditions were defined and converted into computer-readable codes. 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.

(a) Workspace-scaffolding space conflict (Figure 32)

Condition: if a scaffold is installed in a 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 (2) Height difference between Polygon A and Polygon B is within a predefined tolerance (e.g. 2 meter)

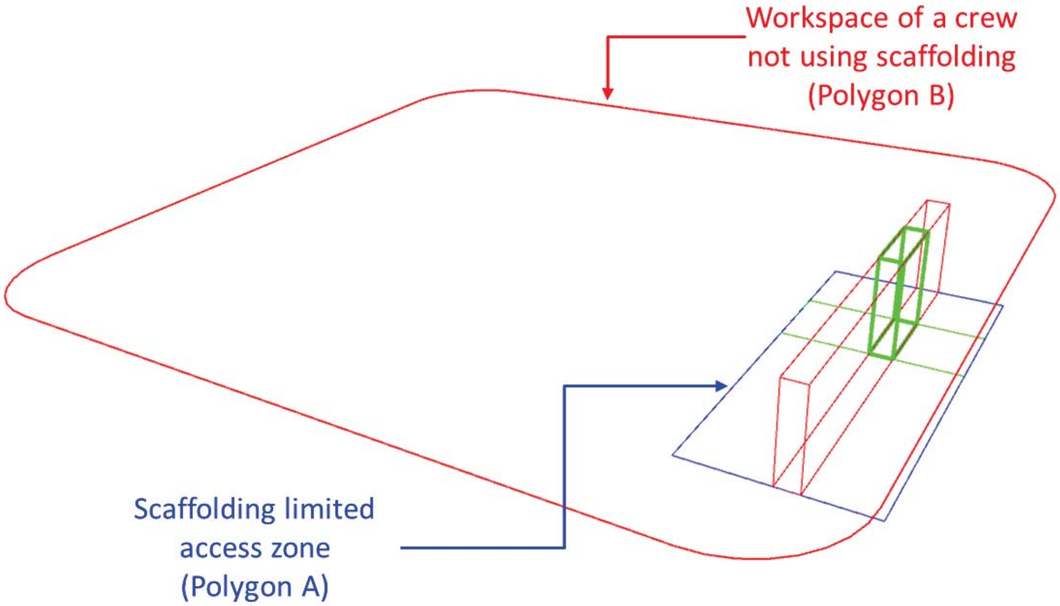


Figure 32: Conflict between a workspace and a scaffolding space

(b) Falling objects from scaffolds (Figure 33)

Condition: if a 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 (2) The height of Polygon A is greater than the height of Polygon B for more than a predefined distance (e.g. 2 meter)

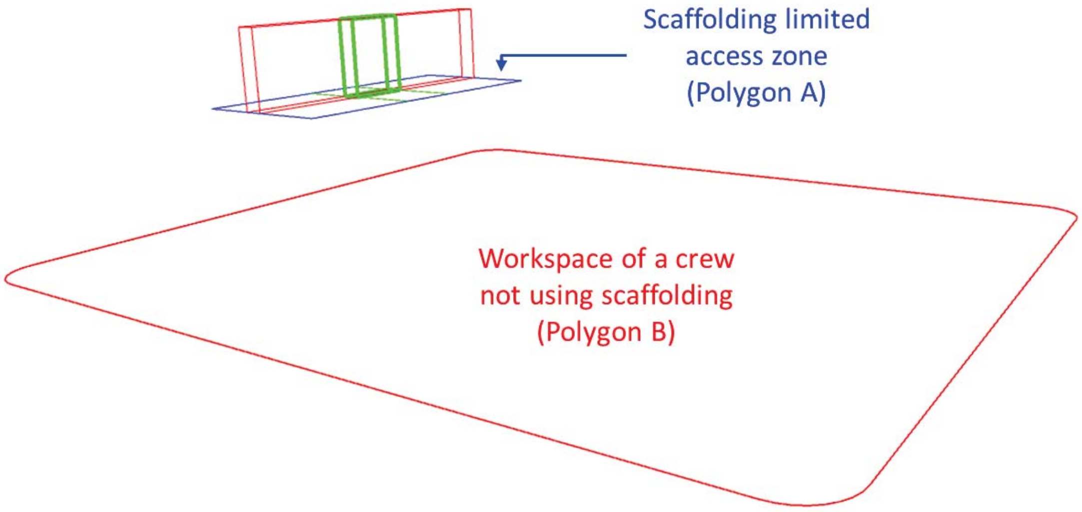


Figure 33: Falling objects from scaffolding

(c) Falling objects to scaffolds (Figure 34)

Condition: if a 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 (2) The height of Polygon B is greater than the height of Polygon A for more than a predefined distance (e.g. 2 meter)

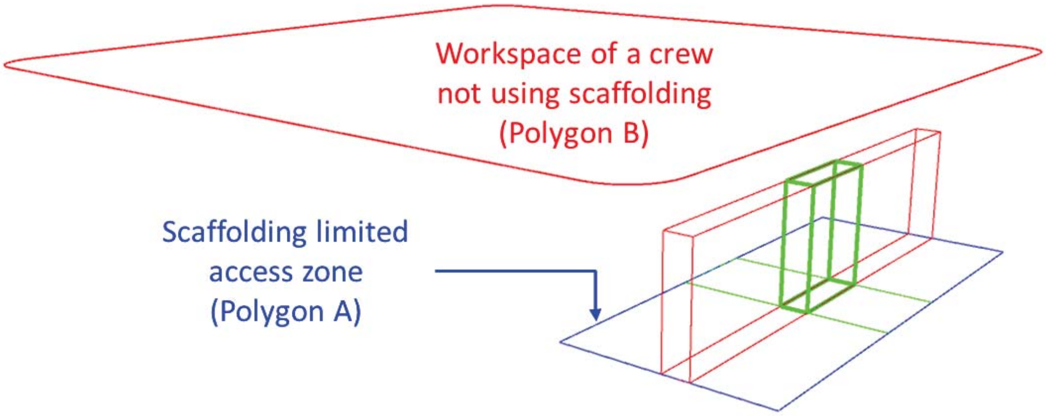


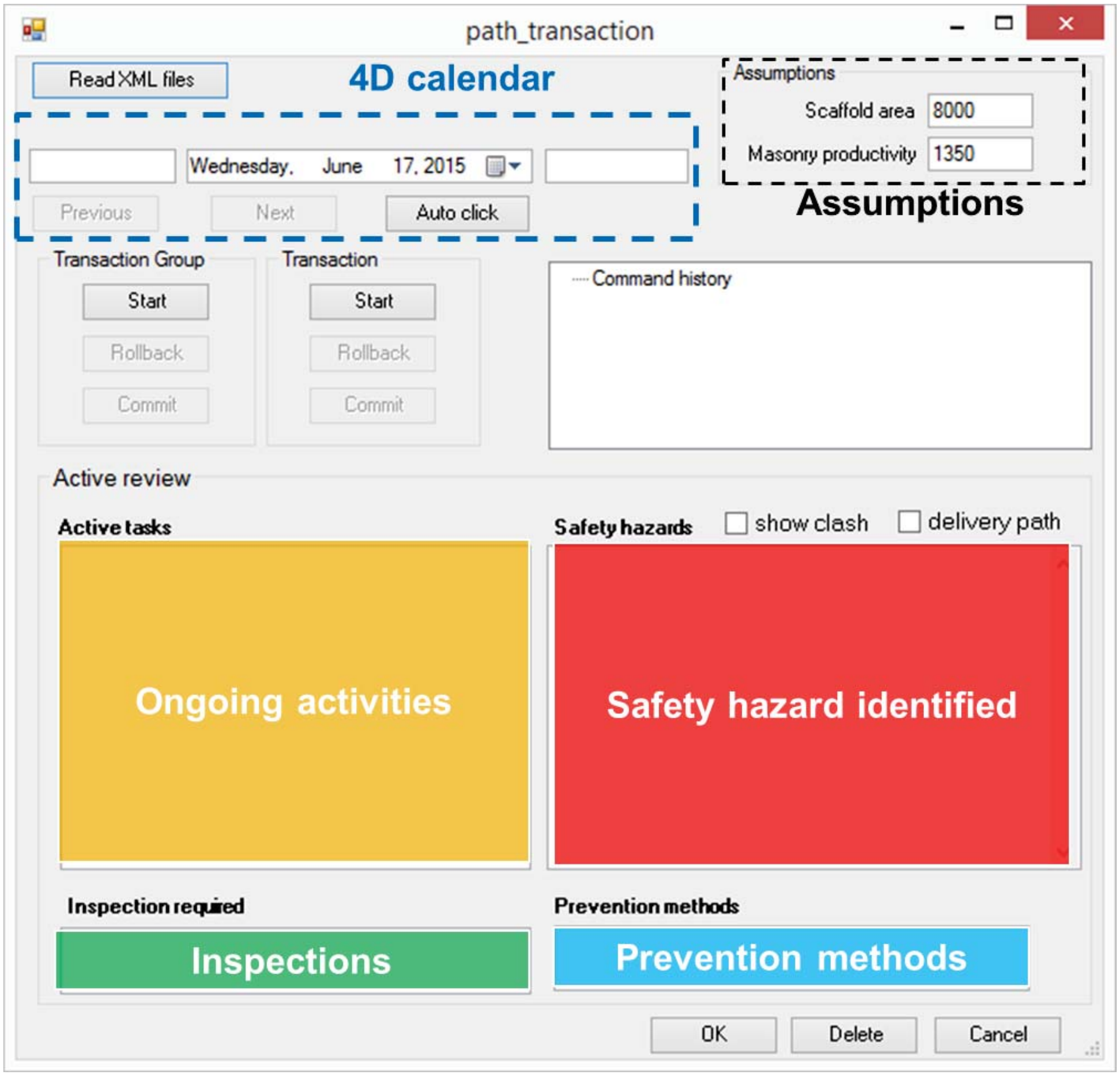
Figure 34: Falling objects to scaffolding

Then, the hazard identification algorithms automatically detect the conditions along the safety simulation. Figure 35 shows the graphical user-interface of the 4D safety simulation, which includes the following main components:

- XML files: XML files for tasks and paths created during user-input preparation step are imported to the simulation.
- 4D calendar: 4D calendar allows the users to choose a day to apply hazard identification algorithms.
- Assumptions: Assumptions about work crews and scaffolds are defined here and used as simulation setting.
- Active tasks: This shows a list of ongoing activities on the day chosen in 4D calendar.
- Safety hazards: Potential safety hazards related to the ongoing tasks are

identified by the algorithms are listed here.

- Inspections: In addition to safety hazards, required scaffolding inspections are listed.
- Prevention methods: In addition to safety hazards, commonly used forms and Job Hazard Analysis (JHA) manual can be incorporated into the system as in Zhang et al. [43].



Wednesday, June 17, 2015

Assumptions

Scaffold area 8000

Masonry productivity 1350

☐ show clash ☐ delivery path

Figure 35: Safety simulation graphical user interface

4. **Scaffolding-related report creation**

   In addition to the simulation results directly viewed from the graphical user interface, various documents and reports can be created to assist in communication between stakeholders. As identified by CII [9, 10], 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 be integrated into the BIM-safety platform. This can eliminate the needs for manual and repeated data input.

6.4 Case study for validation

The BIM-safety platform was developed using commercially available software tools and their APIs (Autodesk Revit and Microsoft Project) and applied in a real construction project. The single-story commercial building construction project shown in Figure 36 needed scaffolds to assist in brick masonry exterior wall construction. 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 construction planning information (BIM, construction schedule, and path plans for major activities) were provided by the general contractor of the project. Figure 37 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.

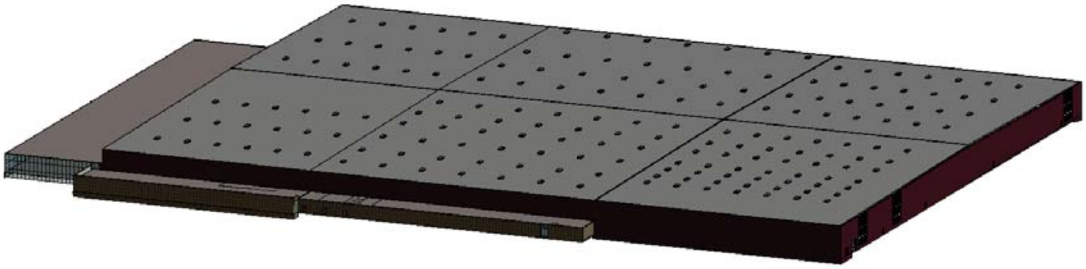
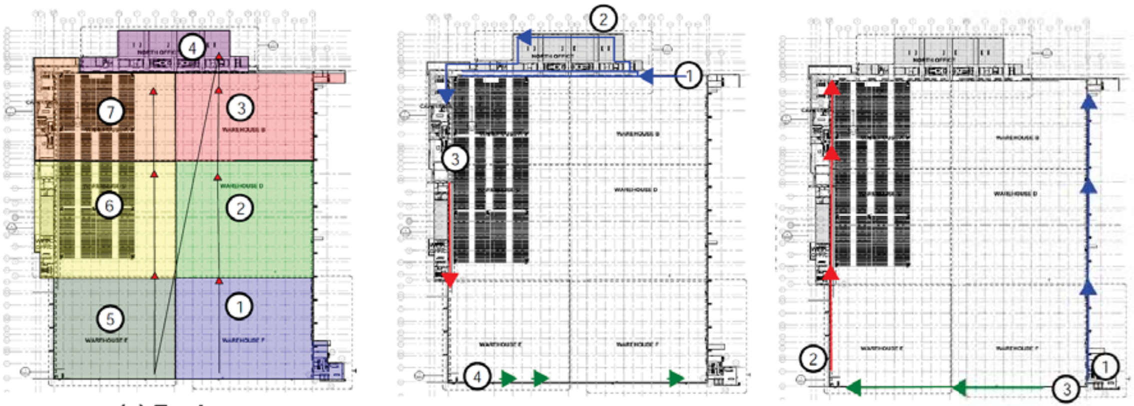


Figure 36: BIM for a real building construction project



(a) Zoning (structural steel, foundation, roofing, and skylight)

(b) Window work path

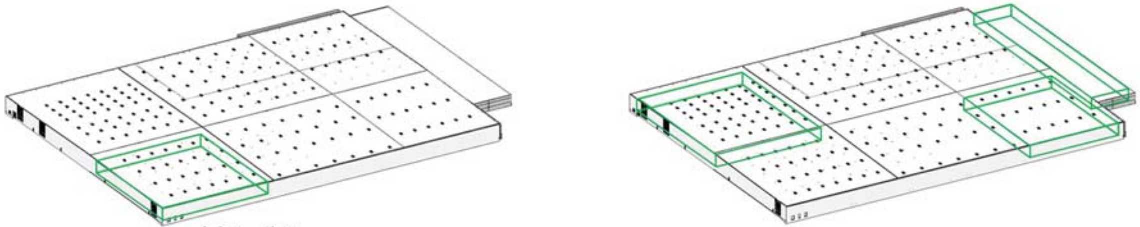
(c) Masonry work path

Figure 37: Zoning and 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:

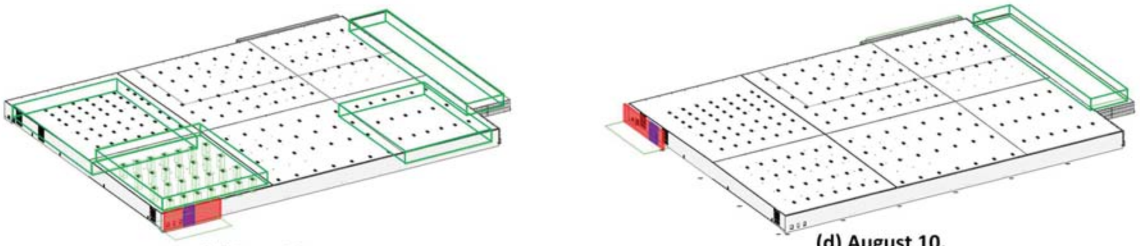
- Daily output: two installation crews (1,350 square feet per day)
- Scaffolding: supported scaffolds used, install 8,000 square feet of scaffold at a time, a scaffolding installation take one day before the scaffold is required

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. Figure 38 shows visualizations of changing construction site conditions using workspaces, scaffolding spaces, and limited access zones during the simulation. For each day, safety hazards were identified and the list was shown in the user interface (Figure 39). A scaffolding installation schedule was also visualized which can assist in timely scaffolding material delivery and installation (Figure 40).



(a) April 14, 2014

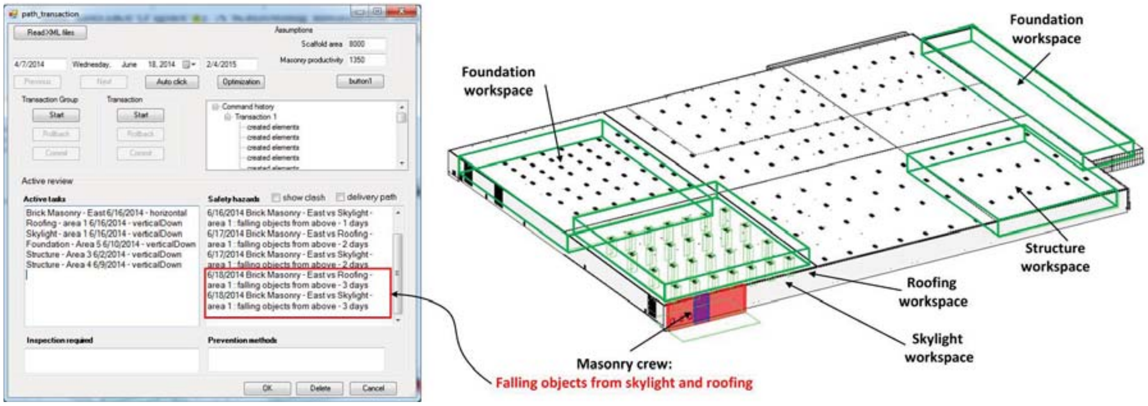
(b) June 10, 2014



(c) June 18, 2014

(d) August 10, 2014

Figure 38: Workspaces, scaffolding spaces generated during BIM-safety simulation



path_transaction

Assumptions

Scaffold area 8000

Masonry productivity 1350

4/7/2014 Wednesday, June 18, 2014 2/4/2015

Transaction Group

Transaction

Command history
  Transaction 1
    created elements
    created elements
    created elements
    created elements

Active review

Active tasks

Brick Masonry - East 6/16/2014 - horizontal
Roofing - area 1 6/16/2014 - verticalDown
Skylight - area 1 6/16/2014 - verticalDown
Foundation - Area 5 6/10/2014 - verticalDown
Structure - Area 3 6/2/2014 - verticalDown
Structure - Area 4 6/9/2014 - verticalDown

Safety hazards ☐ show clash ☐ delivery path

6/16/2014 Brick Masonry - East vs Skylight - area 1 : falling objects from above - 1 days
6/17/2014 Brick Masonry - East vs Roofing - area 1 : falling objects from above - 2 days
6/17/2014 Brick Masonry - East vs Skylight - area 1 : falling objects from above - 2 days
6/18/2014 Brick Masonry - East vs Roofing - area 1 : falling objects from above - 3 days
6/18/2014 Brick Masonry - East vs Skylight - area 1 : falling objects from above - 3 days

Inspection required

Prevention methods

Figure 39: User interface with potential safety hazard list and site condition visualization

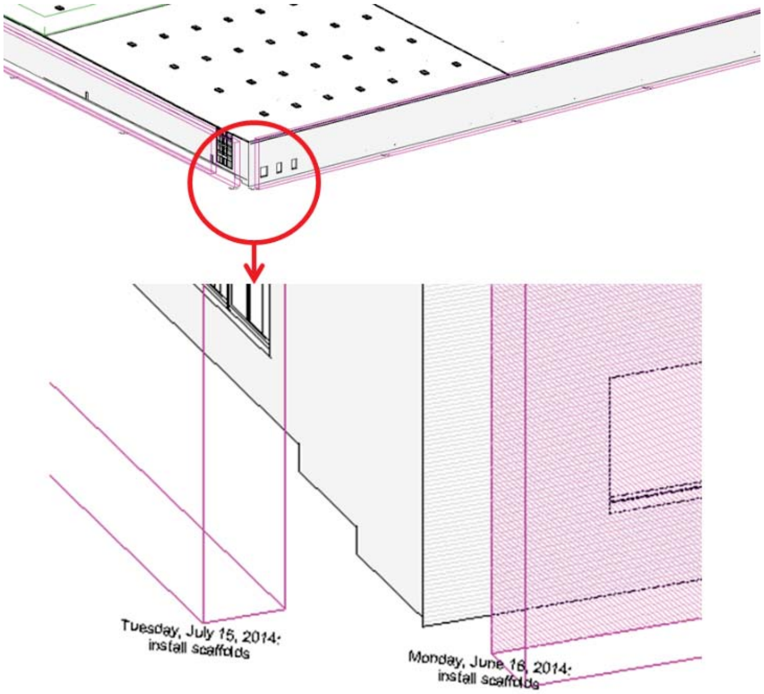
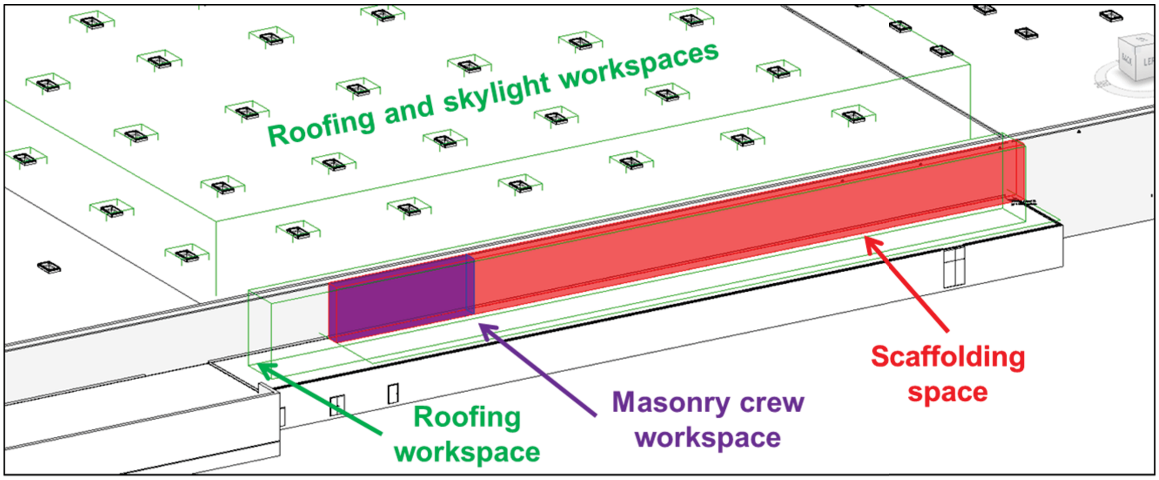


Figure 40: Scaffolding installation schedule visualization

As a result of the simulation, potential safety issues were detected automatically. Many of the potential hazards found from simulation were not identified or even discussed by the construction and safety managers. Even though the safety experts conducted daily safety analysis during construction, they did not document the results of their manual safety analysis. Falling objects to scaffolds from activities above were detected many times from the construction plan. In Figure 39, 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 Figure 41 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 attentions. 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 awareness about the locations of masonry crew and scaffolds, falling objects can directly injure workers or damage the scaffolds that eventually threat the workers. If this result can be communicated by superintendents and related subcontractors before they start daily tasks, the possibility of accidents can potentially be reduced by the increased situation awareness.



Hazard list

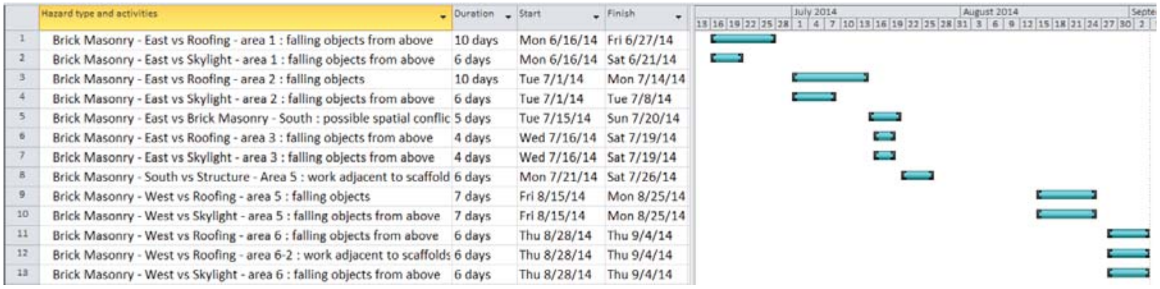
Hazard 1
Time: 8/28/2014 – 9/4/2014
Related activities: “Masonry wall 2nd floor” and “Roofing area 1”
Hazard description: Falling objects from roofing to masonry crew

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

Figure 41: Safety hazards identified in a high risk area

Finally, the safety hazards identified during the simulation were summaries 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 Figure 42.



	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

Figure 42: A schedule of potential hazards

6.5 *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 can identify safety hazards that were not noticed by project and safety managers participating in the case study. Further, 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.

While the test results were promising, several limitations of the proposed approach were recognized. Even though we created workspaces for activities with path plans, this may over-simplify the details of those activities (e.g. roofing and skylight). This problem can be overcome by applying predefined patterns. However, this may need a comprehensive investigation into the behaviors and spatial flows of those activities. Also, the current path creation mechanism requires a user to specify work paths of crew manually. When we consider building geometric conditions that can be complex, 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 can be labor intensive. Also, 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.

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 can 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 simulation assumptions was made for the simulation in this research. The optimization in the future research can automatically apply various crew and temporary structure setting 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 the examples of optimization parameters that can be adjusted automatically.

CHAPTER VII

OPTIMIZATION OF SCAFFOLDING PLAN FOR SAFETY

This chapter introduces an approach to optimize a scaffolding plan for safety. The research presented in this chapter utilizes the accomplishments of previous two chapters: BIM-enabled scaffolding object placement and automated scaffolding-related safety checking. The proposed optimization approach first automatically generates multiple scaffolding planning alternatives. Among the alternatives, users select candidate scaffolding plans that will be reviewed and refined. Finally, users can select one scaffolding plan that will be implemented. By testing all the combinations of decisions related to planning scaffolding, safer scaffolding plans can be generated. Framework, computational algorithms, and case study results are presented.

7.1 Introduction

Construction is conducted by complex interactions of multiple stakeholders. One of the primary goals of construction planning is to coordinate the efforts of the stakeholders toward achieving the maximum productivity without sacrificing worker safety. To establish a safe construction plan, various construction resources, such as work crews, equipment, and temporary structures, need to be considered early in the construction planning stages. It is desirable that potential safety problems are identified in the planning stage so that measures to protect workers can be prepared in advance. It would be optimal to minimize the potential of worker exposures to hazardous conditions through better construction planning. However, creating a safe construction plan can be highly challenging and exhaustive since a construction plan is composed of many decisions that are impacting each other. Furthermore, it is difficult to establish commonly acceptable rules due to the unique situation of each construction project.

Building Information Modeling (BIM) is widely accepted as a standard of practice in construction industry and is changing the way construction and safety is approached [13]. Utilization of BIM can facilitate accurate constructability analysis [23], collaborations between multiple project stakeholders, and enable better safety planning [39]. Also, there are advanced approaches that use BIM for automated safety hazard checking [44]. However, despite the benefits, there still are several limitations that prohibit the achievement of the full potential of BIM for safety planning.

One of the critical limitations is the absence of temporary structures as part of construction and safety planning. The entire construction safety and productivity are greatly impacted by temporary structures, such as scaffolding, formwork, and shoring [34]. Temporary structures need to be planned carefully in a way that avoids any safety hazard or loss of productivity. However, in most construction projects, temporary structures do not appear in drawings, construction schedules, or BIM [18]. Even though many construction projects manually insert temporary structure objects in BIM, they can only be used for the purpose of visualization. The need for manual efforts for safety planning remains existing. It can be extremely labor-intensive and error-prone to establish an optimized temporary structure plan that minimizes potential worker exposures to safety hazards. Among many types of temporary structures, scaffolding is considered as one of the most challenging and wasteful elements of construction management [9, 10]. Like other temporary structures, scaffolds are installed in construction sites without sufficient planning efforts [34]. There are a lot of safety, productivity, constructability, and site coordination problems related to scaffolds [30].

Automated safety hazard checking approaches have the potential to eliminate the current need for excessive manual efforts for safety checking. However, the capability of such safety hazard checking approaches is often limited to identification of potential safety hazards in a given construction plan. A construction plan still needs to be prepared without precise prediction about how each decision (such as zoning, construction method, and temporary structure plan) impacts construction site safety. Since it is impossible to create alternative plans considering all possible combinations of decisions, only a few alternatives of construction plans can be prepared and tested.

Related to planning of temporary structures, similar limitations can be identified. When scaffolding plans are established, several decisions are made by general contractors, subcontractors, and scaffolding subcontractors. Common examples of decisions directly or indirectly related with scaffolds include work sequences, crew size, scaffolding type, etc. Most of these decisions are made based on subjective judgment of engineers and precise calculation of the impact of the decisions are rarely made in the planning stage. Construction planners can mentally simulate only a few plans for scaffolding utilization. As such, current industry practices and existing technology are lacking in methods to enable the creation of safe scaffolding plan by assisting in the planners to make better decisions. As discussed in literature review, optimization of temporary structure plans requires both planning and analysis of temporary structures to be systematically integrated and the objective has been achieve by previous approaches.

In order to address the need for optimization of scaffolding plans, this research develops a temporary structure optimization engine. The optimization engine was developed to assist in construction planners to generate, evaluate, and refine multiple scaffolding planning alternatives. The research introduced in this chapter utilizes the outcomes from the previous chapters to identify potential safety hazards automatically from all the alternatives without the reliance on manual efforts of engineers. The process is presented that comprises an automated generation of alternative plans and manual selection and refinement of candidate plans. A case study has been conducted to demonstrate that the proposed optimization approach can assist in construction planners to create scaffolding plans that are better than the manually created original scaffolding plan. The criteria included safety hazards, cost, and duration. The expected result of applying the optimization approach would be to create safer and more productive scaffolding plans without excessive manual efforts.

7.2 Objective and scope

The objective of this research is to enable optimization of temporary structure plans. This research integrates temporary structures into automated safety planning and optimization using BIM as the integration platform. Among various types of temporary structures, this research focuses on preventing potential safety hazards related to scaffolding. Selection of proper scaffolding types is not included in the scope of this research. To optimize the scaffolding plan, optimization engine was created that generates multiple alternatives of scaffolding plans and to assist in decision making. In order to incorporate scaffolds and simulate daily construction site conditions, the simulation engine was used as part of the optimization engine. The developed optimization engine uses a scaffolding plan as the input to automatically generate multiple alternative scaffolding plans. Then, a user selects a few alternatives that satisfy predefined criteria and refined the plans manually.

Following section presents the framework and methodology for the scaffolding optimization. Case study section presents the implementation of the proposed approach to optimize a scaffolding plan of a real-world construction project. The conclusion section presents the conclusion, limitations, and suggestions for future research studies.

7.3 Development of the proposed scaffolding optimization engine

This section presents the development of the proposed scaffolding optimization approach and computational algorithms to enable the optimization. The section first introduces the optimization framework and then present the development of the computational algorithms.

The frameworks and methodology for the proposed temporary structure safety optimization and simulation engines are presented in this section. Figure 43 shows the framework for the scaffolding safety optimization. The optimization engine is used to generate multiple alternatives of planning scaffolding. As a part of the optimization engine, the safety simulation engine simulates daily construction site conditions and evaluates a scaffolding plans performances on predefined criteria. Details to the five steps are explained.

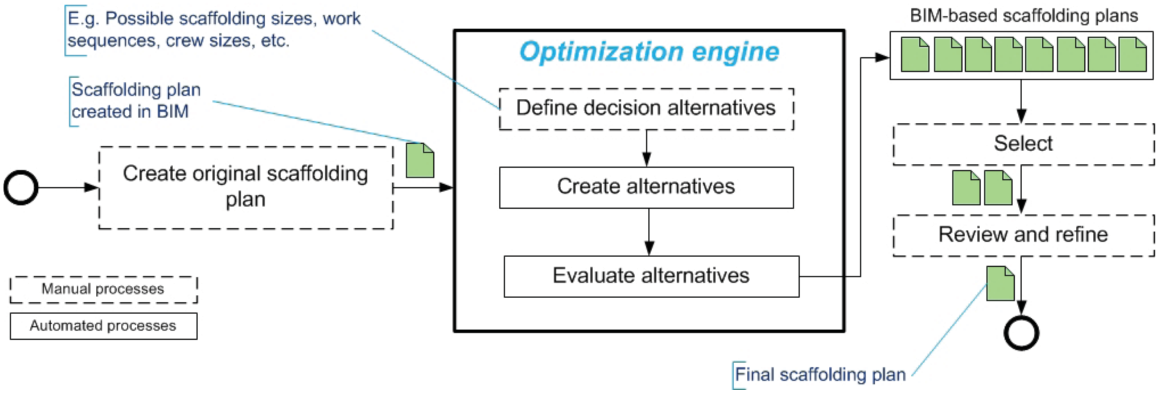


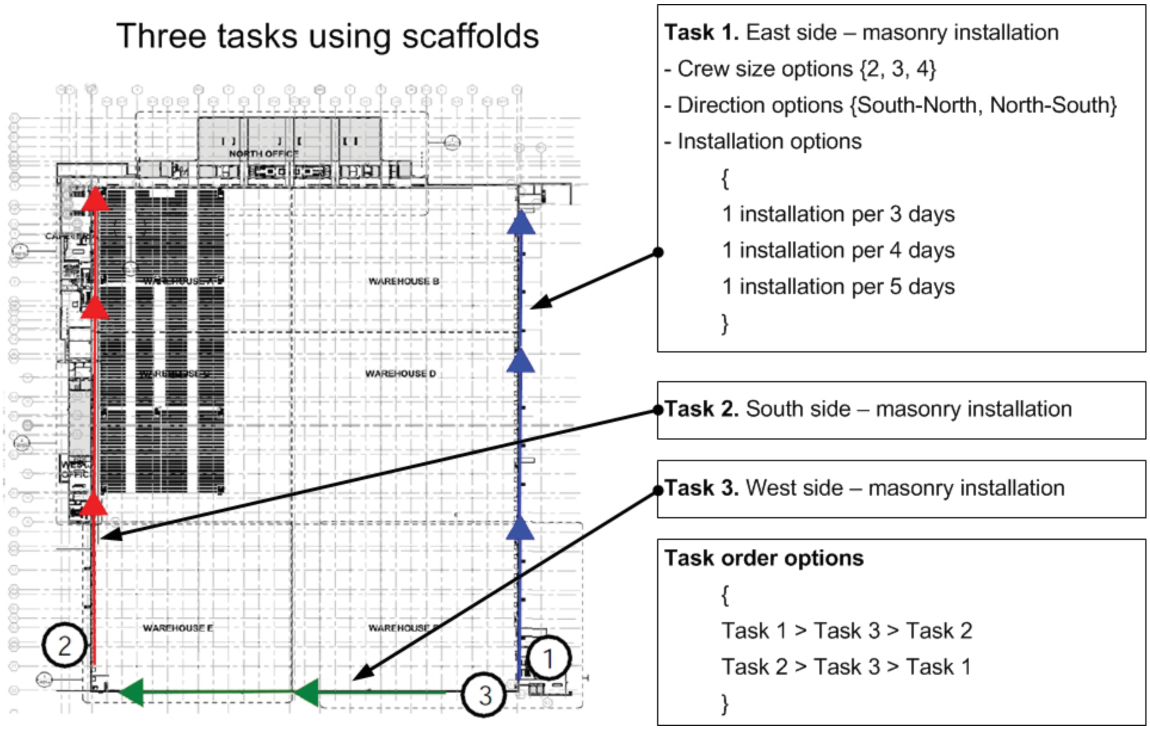
Figure 43: Framework of the proposed Scaffolding Optimization Engine

1. Optimization input preparation

The first step is to prepare user input for the optimization. In addition to creating a 4D BIM and establishing an original scaffolding plan in it, users need to define options for the decisions made while the original scaffolding plan is created (e.g. scaffolding types, sizes, crew sizes, work directions of crews using the scaffolding, etc.). For example, the options for the number of work crews using the scaffolding can be two, three, or four. Work direction for each task can be reversed. Scaffolding can also be installed and demolished more frequently (1 installation per 4 days, 5 days, or 6 days). Depending on the characteristics of different scaffolding types and tasks using the scaffolding, different types of optimization input can be prepared.

Figure 44 illustrates an example scaffolding plan with optimization input information. The work plan in the figure includes three masonry wall construction tasks that need extensive utilization of scaffolding. Arrows along the masonry walls show planned work directions. In the original plan, the masonry crews are required to sequentially complete the construction of masonry walls of East side, South side, and West side. Three crews work at the same time and scaffolding is installed every five days.

Optimization input preparation is done by defining different options for the decisions made for the original scaffolding plan. For example, the number of crews can be two or four instead of three. Work direction for each task can be reversed. Scaffolding can also be installed and demolished more frequently (1 installation per 4 days). The sequence between the three tasks can be reversed (Task 2, Task 3, Task 1).



Task 1. East side – masonry installation
- Crew size options {2, 3, 4}
- Direction options {South-North, North-South}
- Installation options
{
1 installation per 3 days
1 installation per 4 days
1 installation per 5 days
}

Task 2. South side – masonry installation

Task 3. West side – masonry installation

Task order options
{
Task 1 > Task 3 > Task 2
Task 2 > Task 3 > Task 1
}

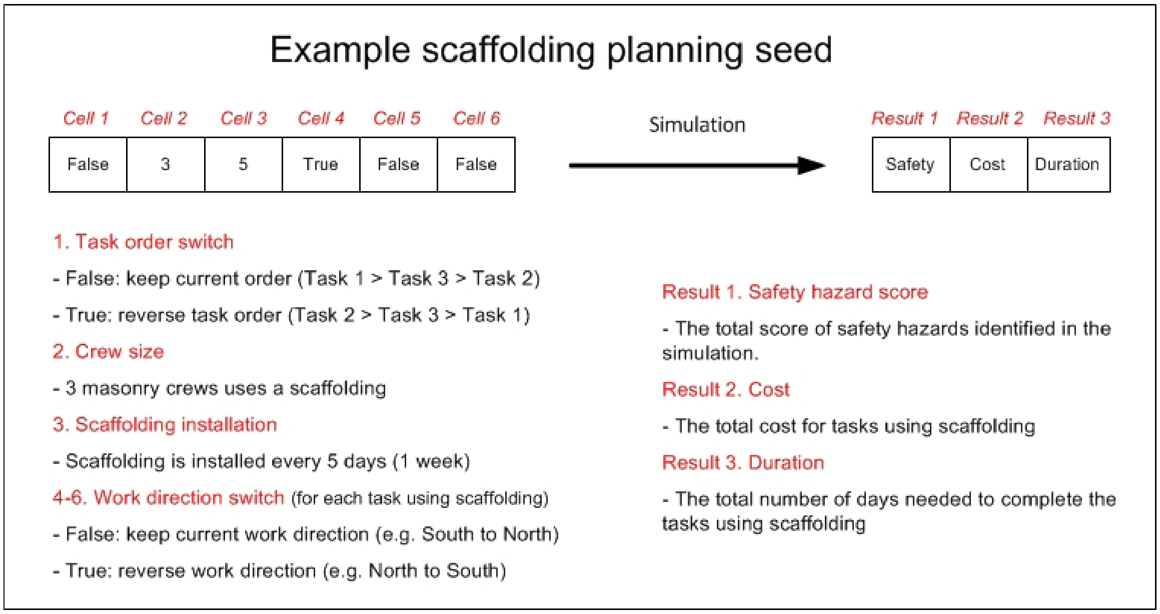
Figure 44: Work paths planned for three masonry construction tasks using scaffolding

2. Creation of scaffolding planning seeds

   After the optimization input has been prepared. The user input needs to be converted into a computer-readable code called scaffolding planning seed. One scaffolding planning seed contains information to create and simulate one scaffold planning alternative. Figure 45 shows an example of scaffolding planning seed created for the plan shown in Figure 44.

   Task order switch cell (cell 1) shows if the sequence between three masonry tasks will be reversed or not. False means the original sequence will be used. Crew size cell (cell 2) shows the number of crews that will work at the same time. Cell 3 shows scaffolding installation pattern. Given that there are five work days in a week, 5 in Cell 3 means a decision to install scaffolds one a week. Cell 4, Cell 5, and Cell 6 represent decisions to switch work directions. The example scaffolding planning seed has three cells for direction switch since there are three masonry construction tasks. If there are many work packages, the number of cells will increase automatically. Scaffolding planning seeds are generated until all possible options are enumerated.

In the next step of scaffolding evaluation, the result cells (Result 1, Result 2, and Result 3) are filled with the simulation results.



1. Task order switch
- False: keep current order (Task 1 > Task 3 > Task 2)
- True: reverse task order (Task 2 > Task 3 > Task 1)

2. Crew size
- 3 masonry crews uses a scaffolding

3. Scaffolding installation
- Scaffolding is installed every 5 days (1 week)

4-6. Work direction switch (for each task using scaffolding)
- False: keep current work direction (e.g. South to North)
- True: reverse work direction (e.g. North to South)

Result 1. Safety hazard score
- The total score of safety hazards identified in the simulation.

Result 2. Cost
- The total cost for tasks using scaffolding

Result 3. Duration
- The total number of days needed to complete the tasks using scaffolding

Figure 45: An example of scaffolding planning seed

3. Automated safety checking using simulation engine

After a set of scaffolding planning seeds are created, scaffolding plans associated with the seeds are generated automatically by the simulation engine. The framework for the safety simulation engine is shown in the previous chapter. The simulation engine read information in the seeds to create scaffolding objects in BIM and then potential safety hazards related to scaffolding are detected. The simulation engine measures performances of a scaffolding plan for criteria other than safety hazards to assist into better decision making of users. The criteria may include scaffolding cost, durations of tasks using scaffolds, etc.

4. Manual selection and visualization

   After all possibilities for planning scaffolds are created and evaluated quantitatively, a few scaffolding plans can be selected manually by the users for further review. Each of the selected options can be visualized in 4D BIM environment where detected safety hazards are visualized.

5. Final selection, refinement, and implementation

   Based on the manual selection and review, a final selection of a scaffolding plan can be made. Then, if needed, the scaffolding plan can be refined before the plan is implemented in the construction project.

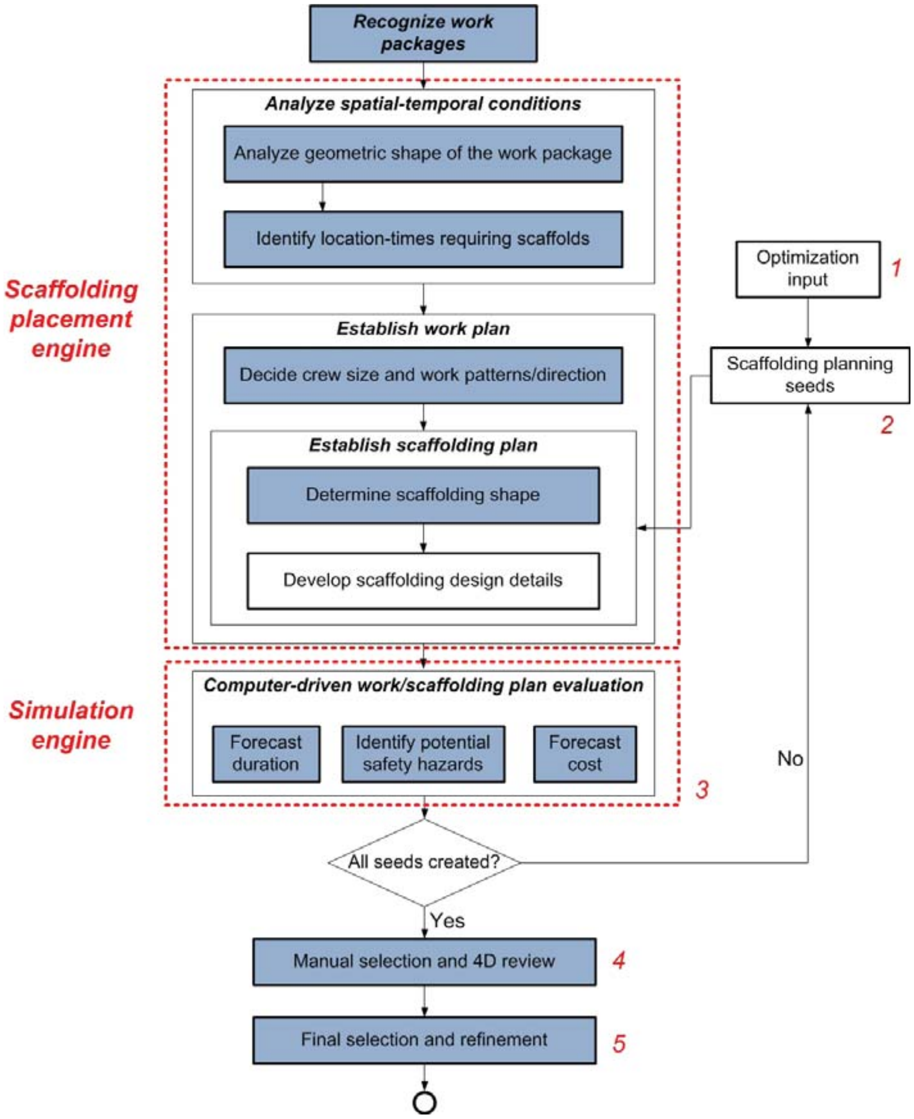


Figure 46: Workflow of the proposed scaffolding optimization engine

Figure 46 illustrates the workflow of the proposed scaffolding optimization engine that incorporates scaffolding placement engine and safety simulation engine. Depending on information in scaffolding planning seeds, both placement of scaffolding and safety simulation are impacted. For example, if the sizes and installation frequency of scaffolding change, shapes and sizes of scaffolding objects created by placement engine are changes. Accordingly, different safety hazards can be detected by the simulation engine. Operations of scaffolding placement engine and simulation engine continue until all possibilities of scaffolding plans are analyzed.

7.4 Implementation and case study

Computational algorithms for simulation and optimization were developed and embedded into 4D BIM system developed for this research. Then, the proposed optimization approach was tested in a real world single-story commercial building construction project that used scaffolds for brick masonry exterior wall construction. The case study was conducted based on close collaboration with the general contractor of the project.

1. Schedule and task detail setup

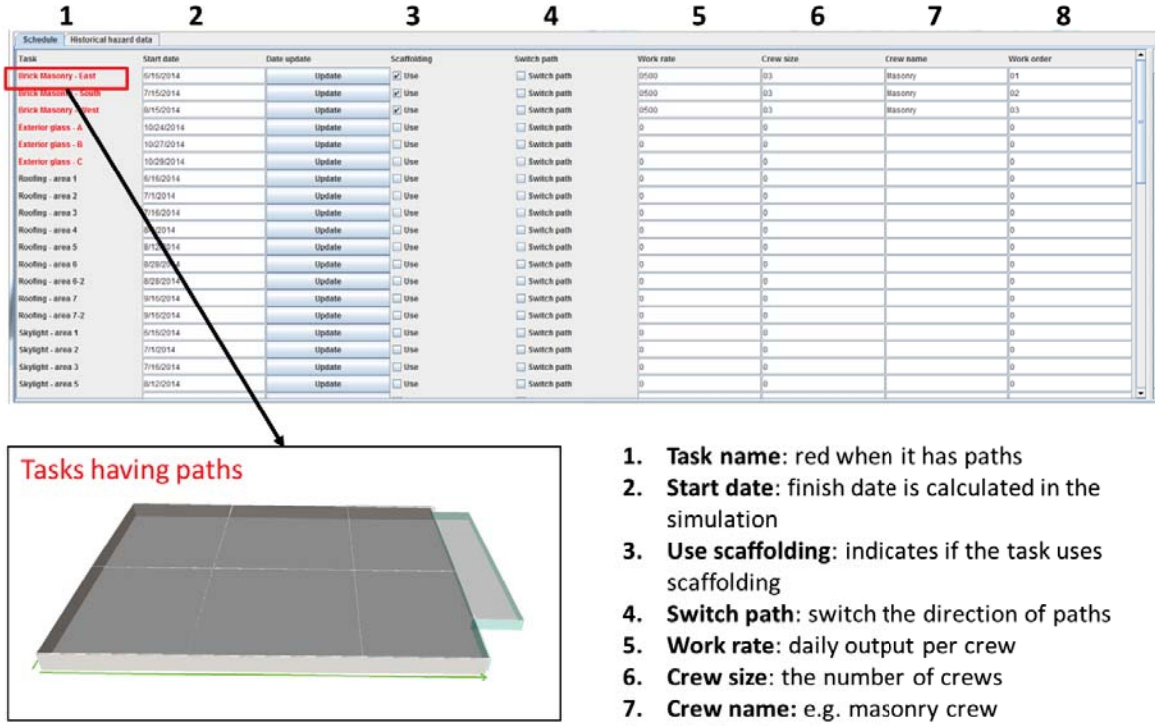
   Figure 47 shows a graphic user interface of the 4D BIM system where the optimization engine was implemented. BIM and construction schedule of the case study project are imported into the system and optimization input can be prepared in the user interface. Input for optimization included work direction, masonry crew size, work order, and scaffolding installation pattern.

   (a) Work direction: Work directions are planned spatial flows of work crews using the scaffolds. Since daily workspaces occupied by the crews and scaffolds can change depending on different work directions, construction site conditions and thus potential safety hazards change. Alternative decisions are automatically created by flipping the directional vectors of the directions.

   (b) Masonry crew size: Given that the productivity of each crew is the same, the speed of masonry work is determined by the number of crews. Locations of daily workspaces and sizes of the workspaces are impacted by this decision. Actual crew size in the project was three. In the optimization, crew sizes of two, three, and four have been used.

(c) Work order: Work order is the sequence among three masonry wall construction tasks. In the original construction schedule, brick masonry construction is completed following the order of East, South, and West exterior walls. During the optimization, a reversed order (West, South, and East) is simulated.

(d) Scaffolding installation pattern: Scaffolding installation pattern determines how frequently scaffolding is installed in the construction site. If the value is four, a scaffolding is used for four days once it is installed. In other words, the size of the scaffolding needs to be equivalent to five workspaces. For optimization, three, four, and five were used as options for scaffolding installation.



Task	Start date	Date update	Scaffolding	Switch path	Work rate	Crew size	Crew name	Work order
Brick Masonry - East	6/16/2014	Update	☑ Use	☐ Switch path	0500	03	Masonry	01
Brick Masonry - South	7/15/2014	Update	☑ Use	☐ Switch path	0500	03	Masonry	02
Brick Masonry - West	8/15/2014	Update	☑ Use	☐ Switch path	0500	03	Masonry	03
Exterior glass - A	10/24/2014	Update	☐ Use	☐ Switch path	0	0		0
Exterior glass - B	10/27/2014	Update	☐ Use	☐ Switch path	0	0		0
Exterior glass - C	10/29/2014	Update	☐ Use	☐ Switch path	0	0		0
Roofing - area 1	6/16/2014	Update	☐ Use	☐ Switch path	0	0		0
Roofing - area 2	7/1/2014	Update	☐ Use	☐ Switch path	0	0		0
Roofing - area 3	7/16/2014	Update	☐ Use	☐ Switch path	0	0		0
Roofing - area 4	8/[illegible]/2014	Update	☐ Use	☐ Switch path	0	0		0
Roofing - area 5	8/12/2014	Update	☐ Use	☐ Switch path	0	0		0
Roofing - area 6	8/28/2014	Update	☐ Use	☐ Switch path	0	0		0
Roofing - area 6-2	8/28/2014	Update	☐ Use	☐ Switch path	0	0		0
Roofing - area 7	9/16/2014	Update	☐ Use	☐ Switch path	0	0		0
Roofing - area 7-2	9/16/2014	Update	☐ Use	☐ Switch path	0	0		0
Skylight - area 1	6/16/2014	Update	☐ Use	☐ Switch path	0	0		0
Skylight - area 2	7/1/2014	Update	☐ Use	☐ Switch path	0	0		0
Skylight - area 3	7/16/2014	Update	☐ Use	☐ Switch path	0	0		0
Skylight - area 5	8/12/2014	Update	☐ Use	☐ Switch path	0	0		0

1. **Task name**: red when it has paths
2. **Start date**: finish date is calculated in the simulation
3. **Use scaffolding**: indicates if the task uses scaffolding
4. **Switch path**: switch the direction of paths
5. **Work rate**: daily output per crew
6. **Crew size**: the number of crews
7. **Crew name:** e.g. masonry crew
8. **Work order**: the order between tasks done by the same crew

Figure 47: Schedule and task detail setup

2. Safety hazard rating setup

   Also, in collaboration with safety managers of the project, different scores were prepared for different types of safety hazards related to temporary structures. The purpose is to evaluate the overall score for a schedule. Therefore, a score needs to be assigned to each type of safety hazard. By doing so, detected safety hazards can be quantitatively evaluated and summed up during the simulation. With the safety experts, scores have been decided based on their professional judgment and understanding about the project (0-2= Minimal/Low Safety Exposure, 9= High/Extreme Safety Exposure). These scores (Table 2) were used to evaluate the overall safety level of a scaffolding plan by a single digit.

Table 2: Scores for different hazard types

Hazard type	Hazard description	Score
Type 1	Falling objects to workspace	8
Type 2	Falling objects to scaffolding	6
Type 3	Falling objects to scaffolding installation workspace	7
Type 4	Spatial conflicts between workspaces	5
Type 5	Spatial conflicts between scaffolding space and other workspace	3
Type 6	Spatial conflicts between scaffolding installation workspace and other worker space	4

Six types of hazards related to scaffolds were detected automatically. Descriptions are provided.

- Hazard type 1
    - Name: falling objects to workspace
    - Description: falling objects from a vertically higher workspace to a lower workspace occupied by another work crew
    - Score: 8
- Hazard type 2
    - Name: falling objects to scaffolding
    - Description: falling objects from a vertically higher workspace to a scaffolding used by another work crew
    - Score: 6

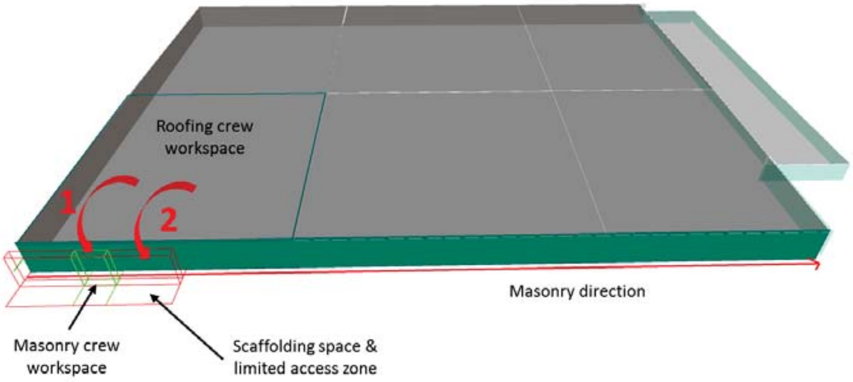


Figure 48: Hazard type 1 and type 2

- Hazard type 3
  - Name: falling objects to scaffolding installation workspace
  - Description: falling objects from a vertically higher workspace to a workspace used for scaffolding installation
  - Score: 7

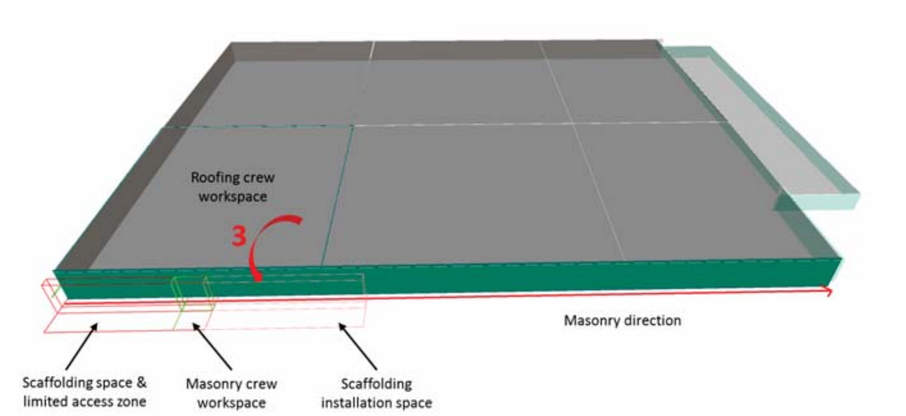


Figure 49: Hazard type 3

- Hazard type 4
  - Name: spatial conflicts between workspaces
  - Description: workspaces of multiple work crews overlapping
  - Score: 5
- Hazard type 5
  - Name: spatial conflicts between scaffolding space and other workspace
  - Description: a crew needs to work when there is a scaffold in the workspace, equivalent to falling objects from scaffold
  - Score: 3

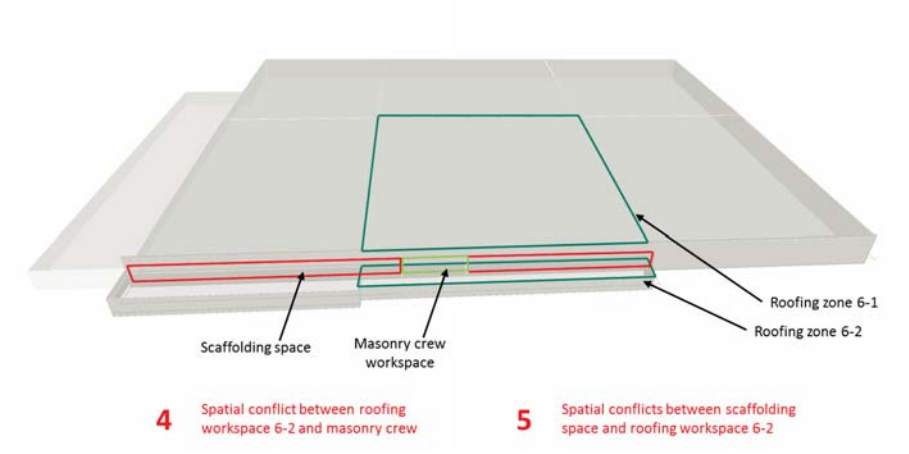


Figure 50: Hazard type 4 and type 5

- Hazard type 6
  - Name: spatial conflicts between scaffolding installation workspace and other worker space
  - Description: the same space is used for scaffolding installation and another work crew

- Score: 4

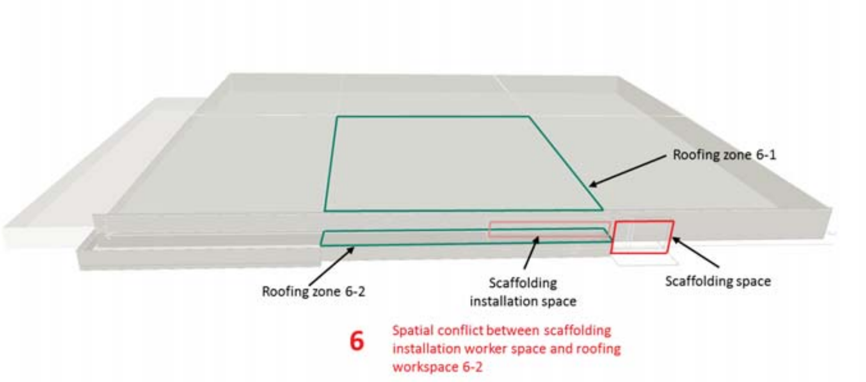


Figure 51: Hazard type 6

3. Objective function setup

   The project team intended to evaluate each scaffolding plan options based on multiple criteria not limited to safety hazard score. Total cost for masonry wall construction and the total number of days required to complete all the masonry wall construction were evaluated based on the following methods.

   - Masonry construction cost

     Masonry cost = Scaffolding cost + Crew labor & material cost

     Scaffolding cost = Scaffolding length × \$200 + Cost for site visits

     Cost for site visits = \$100 per visit

     Crew labor & material cost = (\$2.5+\$3.5×crew size)×masonry quantity

   - Masonry duration

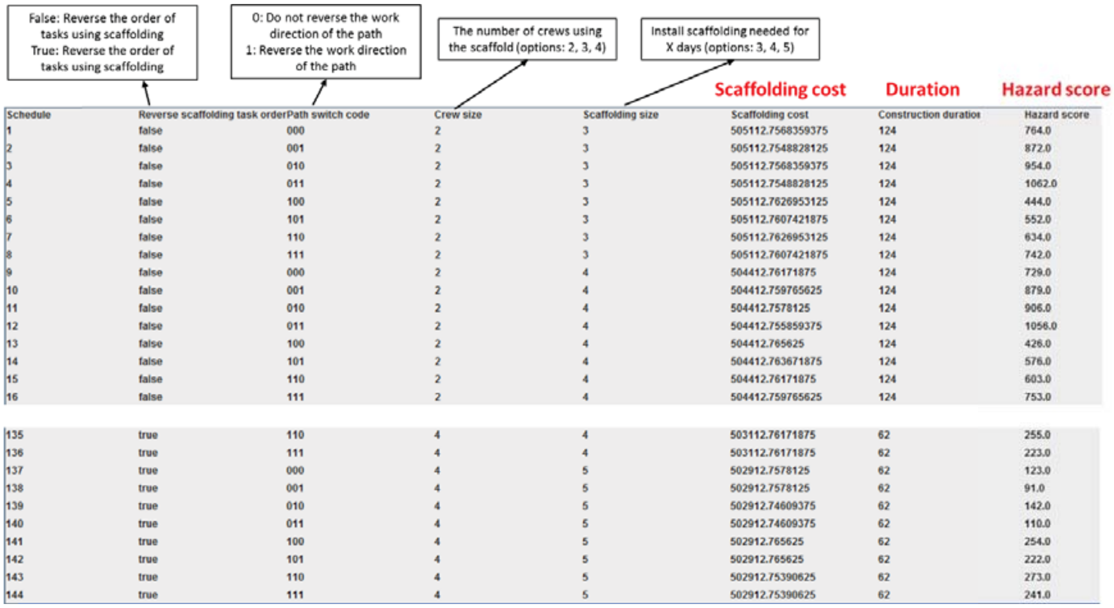
     The total days needed to complete tasks using scaffolds is calculated during the simulation.

- Total safety hazard score

  Safety hazard score is calculated when potential safety hazards are detected during the simulation using hazard score.

4. Run simulation

   Based on the optimization input prepared by the construction managers and safety inspectors of the project, the optimization system created the total of 144 scaffolding planning options (Figure 52). The project team used three criteria (scaffolding cost, duration, and hazard score) to select candidate scaffolding plans. Figure 53 shows the scaffolding plan alternatives in duration-cost plot. Due to many alternatives having similar performances in cost and duration, diversity of the alternatives were able to be better shown in a 3D scatterplot (Figure 54).



Schedule	Reverse scaffolding task order	Path switch code	Crew size	Scaffolding size	Scaffolding cost	Construction duratio	Hazard score
1	false	000	2	3	505112.7568359375	124	764.0
2	false	001	2	3	505112.7548828125	124	872.0
3	false	010	2	3	505112.7568359375	124	954.0
4	false	011	2	3	505112.7548828125	124	1062.0
5	false	100	2	3	505112.7626953125	124	444.0
6	false	101	2	3	505112.7607421875	124	552.0
7	false	110	2	3	505112.7626953125	124	634.0
8	false	111	2	3	505112.7607421875	124	742.0
9	false	000	2	4	504412.76171875	124	729.0
10	false	001	2	4	504412.759765625	124	879.0
11	false	010	2	4	504412.7578125	124	906.0
12	false	011	2	4	504412.755859375	124	1056.0
13	false	100	2	4	504412.765625	124	426.0
14	false	101	2	4	504412.763671875	124	576.0
15	false	110	2	4	504412.76171875	124	603.0
16	false	111	2	4	504412.759765625	124	753.0
135	true	110	4	4	503112.76171875	62	255.0
136	true	111	4	4	503112.76171875	62	223.0
137	true	000	4	5	502912.7578125	62	123.0
138	true	001	4	5	502912.7578125	62	91.0
139	true	010	4	5	502912.74609375	62	142.0
140	true	011	4	5	502912.74609375	62	110.0
141	true	100	4	5	502912.765625	62	254.0
142	true	101	4	5	502912.765625	62	222.0
143	true	110	4	5	502912.75390625	62	273.0
144	true	111	4	5	502912.75390625	62	241.0

Figure 52: Options and objective values of 144 scaffolding alternatives

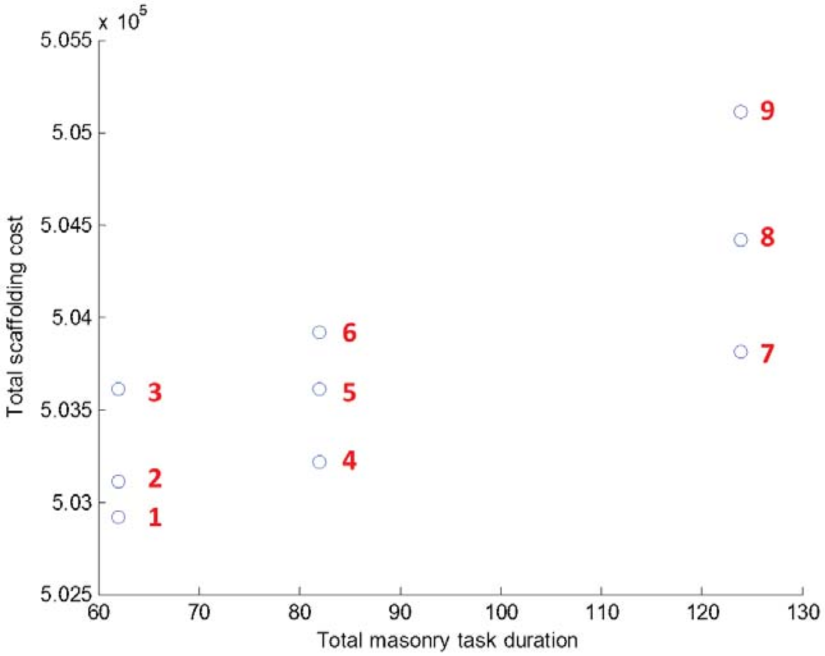


Figure 53: 144 scaffolding plan alternatives in duration-cost plot

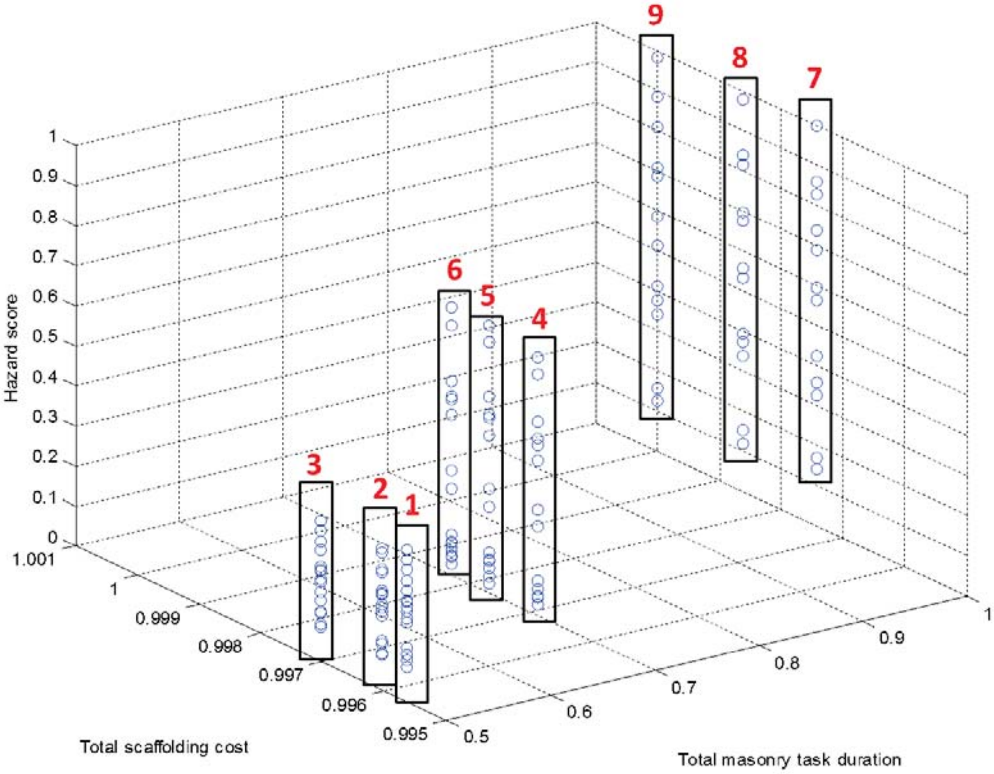


Figure 54: 3D scatterplot of 144 scaffolding plan alternatives

5. Performance-based section and review in 4D BIM

   Construction managers and safety managers participating in this case study selected scaffolding plan alternatives based on their performances in the criteria. As shown in Figure 55, six alternative were selected for review in 4D BIM environment. Alternatives with durations longer than 120 days were excluded. Alternatives with low hazard scores were selected from group 1 and group 4. Even though alternative number 43 and 69 have high hazard scores, they were chose intentionally to review diverse possibilities.

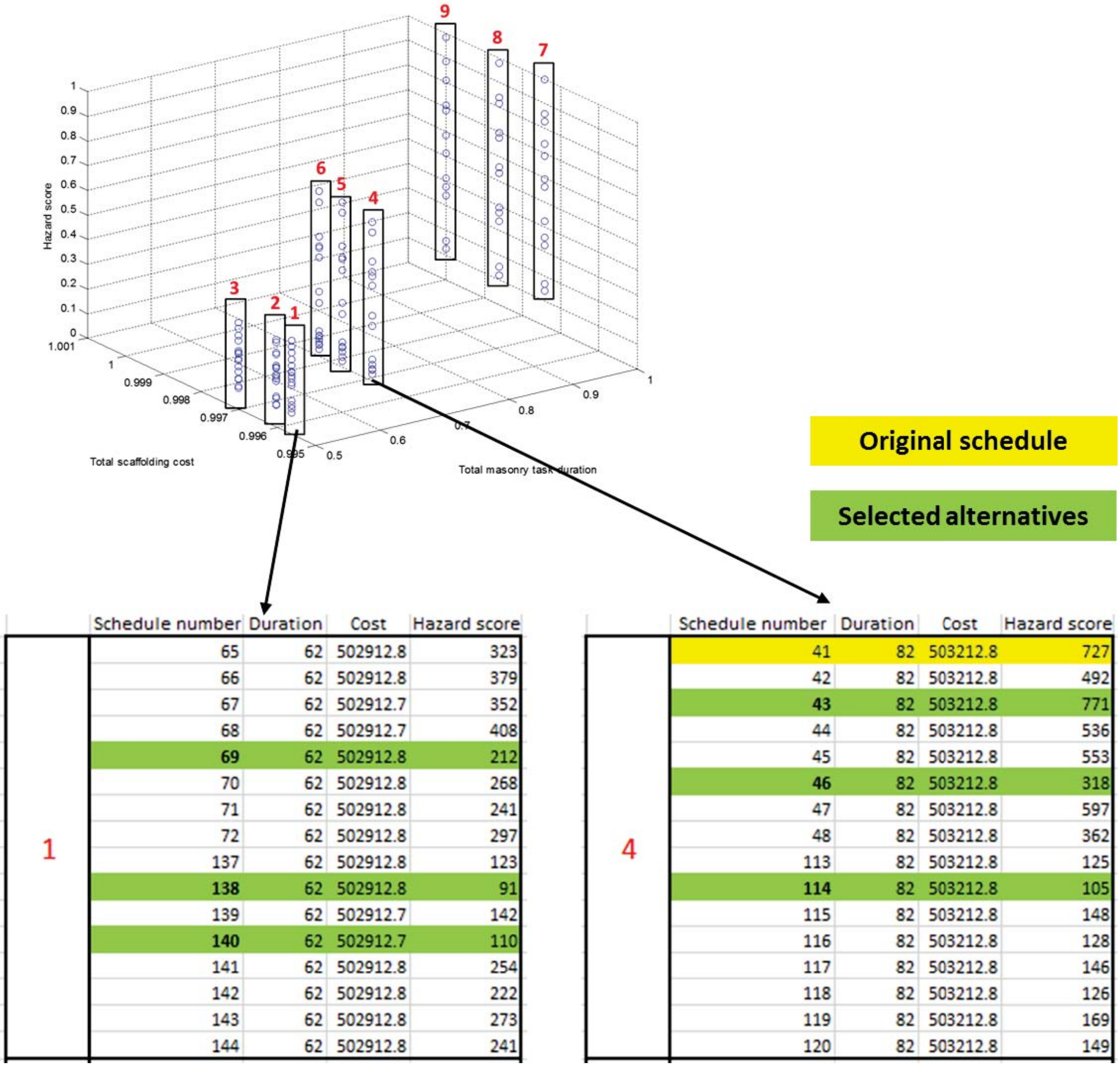
6. Automatically generated reports

For each alternative, a performance review report can be generated automatically. Figure 56 shows a report for the original scaffolding plan. In the plan view of the report, all the locations with potential hazards are highlighted by red boxes to give an instant insight into the potential hazards associated with the scaffolding plan. Also, daily safety hazard reports can be generated as shown on the left. Figure 57 and Figure 58 summarize the scaffolding utilization strategies and performances of the six selected alternatives.

7. Professional review of selected alternatives

   In this way, construction managers and safety managers reviewed the selected alternatives using the reports and simulation in 4D BIM environment. While reviewing the alternatives, subjective judgment of the managers were used to re-evaluate the selected scaffolding plans. Based on the review of the six alternatives, plans (alternative 43, 46, 69, and original plan) with a reversed order (West, South, and East) had lower hazard scores than the plans (alternative 114, 138, and 140) with an original order (East, South, and West). Depending on the work directions, sizes of scaffolding, and number of work crews, there were slight hazard score differences among the plans with lower scores. Constructability review of the construction managers concluded that the reversed work order can implemented without any significant changes to plans for other tasks. As a result, alternative 140 was selected as the optimal scaffolding plan suitable for this project. Among alternative 114, 138, and 140, alternative 140 was selected because of the continuity of the work paths that movement of masonry crews along the walls can be minimized.

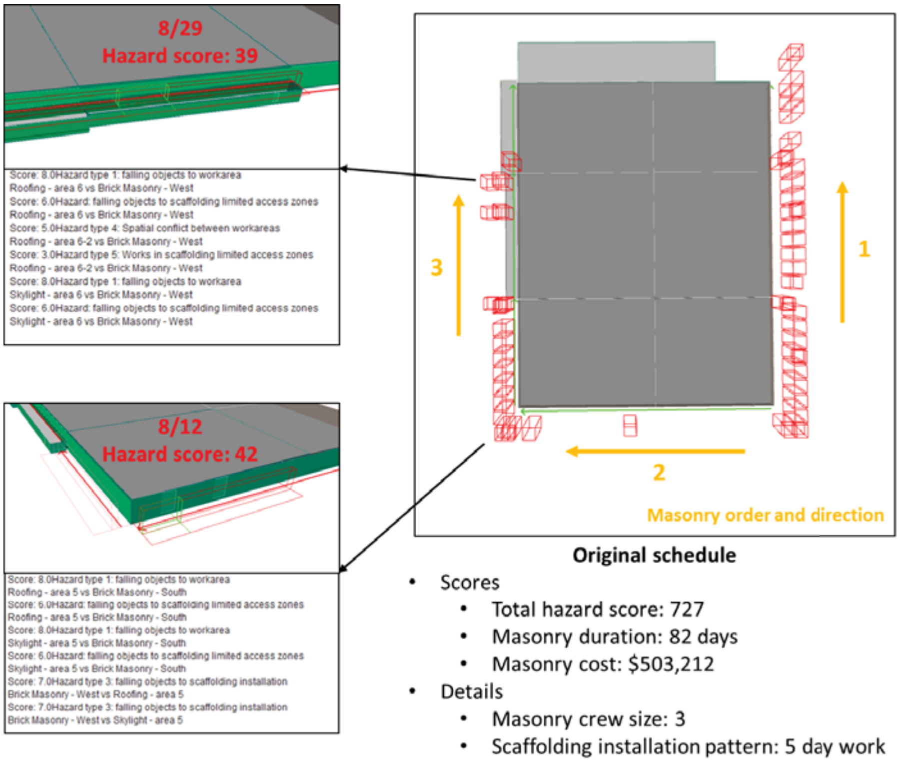
   Most of the hazards were falling objects to scaffolding and workspaces from roofing crews. Potential for these hazards can be minimized by controlling the workflows of roofing crews within their workspaces. Potential falling objects to scaffolding can be prevented by limiting any activity around and above the installation crews.



	Schedule number	Duration	Cost	Hazard score
1	65	62	502912.8	323
	66	62	502912.8	379
	67	62	502912.7	352
	68	62	502912.7	408
	69	62	502912.8	212
	70	62	502912.8	268
	71	62	502912.8	241
	72	62	502912.8	297
	137	62	502912.8	123
	138	62	502912.8	91
	139	62	502912.7	142
	140	62	502912.7	110
	141	62	502912.8	254
	142	62	502912.8	222
	143	62	502912.8	273
	144	62	502912.8	241

	Schedule number	Duration	Cost	Hazard score
4	41	82	503212.8	727
	42	82	503212.8	492
	43	82	503212.8	771
	44	82	503212.8	536
	45	82	503212.8	553
	46	82	503212.8	318
	47	82	503212.8	597
	48	82	503212.8	362
	113	82	503212.8	125
	114	82	503212.8	105
	115	82	503212.8	148
	116	82	503212.8	128
	117	82	503212.8	146
	118	82	503212.8	126
	119	82	503212.8	169
	120	82	503212.8	149

Figure 55: Performance-based selection of alternatives



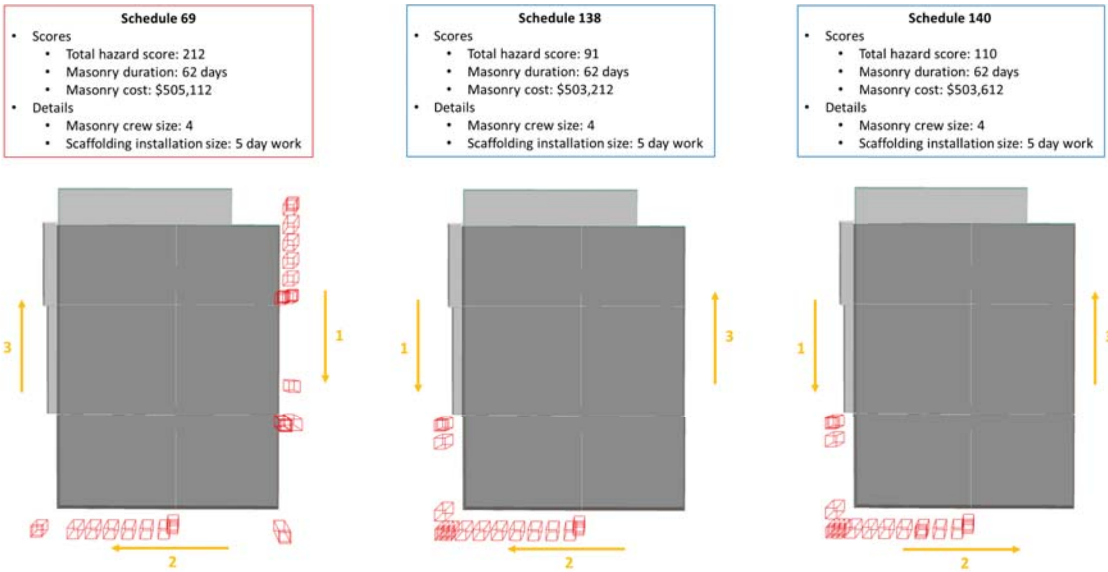
Score: 8.0Hazard type 1: falling objects to workarea
Roofing - area 6 vs Brick Masonry - West
Score: 6.0Hazard: falling objects to scaffolding limited access zones
Roofing - area 6 vs Brick Masonry - West
Score: 5.0Hazard type 4: Spatial conflict between workareas
Roofing - area 6-2 vs Brick Masonry - West
Score: 3.0Hazard type 5: Works in scaffolding limited access zones
Roofing - area 6-2 vs Brick Masonry - West
Score: 8.0Hazard type 1: falling objects to workarea
Skylight - area 6 vs Brick Masonry - West
Score: 6.0Hazard: falling objects to scaffolding limited access zones
Skylight - area 6 vs Brick Masonry - West

Score: 8.0Hazard type 1: falling objects to workarea
Roofing - area 5 vs Brick Masonry - South
Score: 6.0Hazard: falling objects to scaffolding limited access zones
Roofing - area 5 vs Brick Masonry - South
Score: 8.0Hazard type 1: falling objects to workarea
Skylight - area 5 vs Brick Masonry - South
Score: 6.0Hazard: falling objects to scaffolding limited access zones
Skylight - area 5 vs Brick Masonry - South
Score: 7.0Hazard type 3: falling objects to scaffolding installation
Brick Masonry - West vs Roofing - area 5
Score: 7.0Hazard type 3: falling objects to scaffolding installation
Brick Masonry - West vs Skylight - area 5

Original schedule

- Scores
  - Total hazard score: 727
  - Masonry duration: 82 days
  - Masonry cost: $503,212
- Details
  - Masonry crew size: 3
  - Scaffolding installation pattern: 5 day work

Figure 56: Original schedule with detected unsafety zones visualized



Schedule 69

- Scores
  - Total hazard score: 212
  - Masonry duration: 62 days
  - Masonry cost: $505,112
- Details
  - Masonry crew size: 4
  - Scaffolding installation size: 5 day work

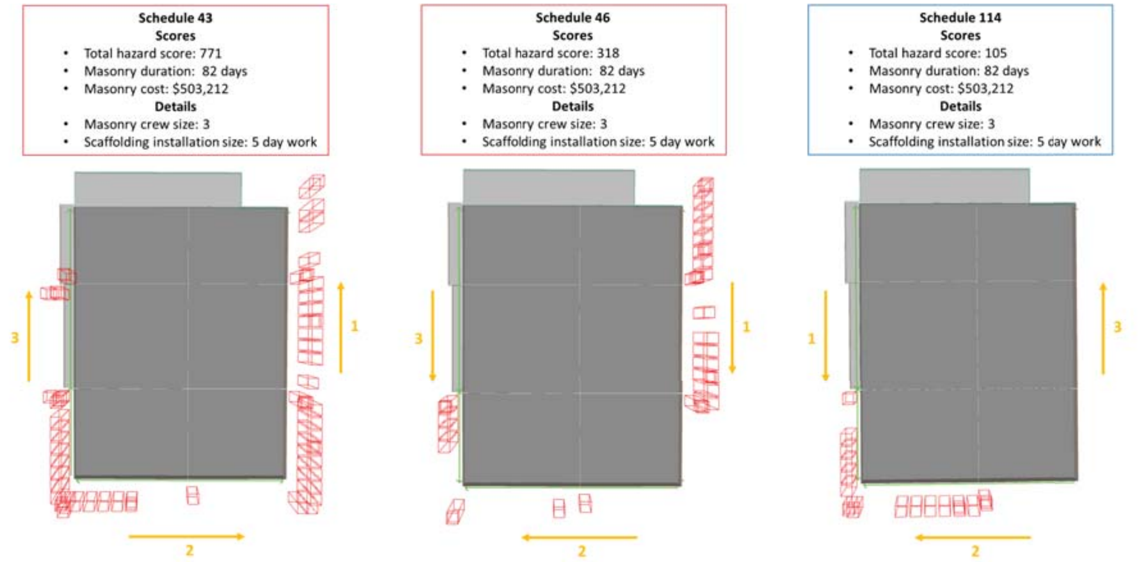
Schedule 138

- Scores
  - Total hazard score: 91
  - Masonry duration: 62 days
  - Masonry cost: $503,212
- Details
  - Masonry crew size: 4
  - Scaffolding installation size: 5 day work

Schedule 140

- Scores
  - Total hazard score: 110
  - Masonry duration: 62 days
  - Masonry cost: $503,612
- Details
  - Masonry crew size: 4
  - Scaffolding installation size: 5 day work

Figure 57: Scheduling alternative 69, 138, and 140 with detected unsafety zones visualized



Schedule 43

Scores

- Total hazard score: 771
- Masonry duration: 82 days
- Masonry cost: $503,212

Details

- Masonry crew size: 3
- Scaffolding installation size: 5 day work

Schedule 46

Scores

- Total hazard score: 318
- Masonry duration: 82 days
- Masonry cost: $503,212

Details

- Masonry crew size: 3
- Scaffolding installation size: 5 day work

Schedule 114

Scores

- Total hazard score: 105
- Masonry duration: 82 days
- Masonry cost: $503,212

Details

- Masonry crew size: 3
- Scaffolding installation size: 5 day work

Figure 58: Scheduling alternative 43, 46, and 114 with detected unsafety zones visualized

7.5 Results and discussion

This paper presented a method to integrate temporary structures into automated safety planning and optimization in BIM. The framework, algorithms, and a case study were presented. Implementation of this approach in a real world construction project demonstrated its capabilities to generate a wide range of scaffolding planning alternatives based on the user input and eventually to assist in informed decision making for scaffolding safety planning. Construction and safety managers agreed on the potential benefits of the proposed optimization of scaffolding plans. The original masonry wall construction plan incorporating scaffolding utilization has been optimized into a plan that contains a different work order, work directions, scaffolding sizes, and the number of work crews. According to the professionals who participated in the case study, the optimized plan clearly is a safer scaffolding plan that expose workers to less hazardous conditions compared to the original plan developed by them. However, their testimonials show that it is extremely challenging to explore and evaluate various possibilities of planning scaffolds in the real world construction planning. The case study demonstrated the capability of the proposed optimization approach to assist in planners to have a clearer insight into available ways to construct the same structure and make informed decisions for safety. Even though this research focused on safety hazards associated with scaffolding used for masonry contractors only, future research would be needed to comprise various types of tasks and other temporary structures into the automated safety hazard analysis. Further research can be conducted to integrate more sofisticated optimization algorithms. In this research, available alternatives were created by enumerating all possible combinations. However, exhaustive enumeration can be computationally expensive when the simulation becomes more complex by integrating other types of temporary structures and incorporating scheduling and contructability logics. Multi-objective optimization approaches, such as [22], can be integrated to the research in this thesis.

CHAPTER VIII

VALIDATION OF SCAFFOLDING PLACEMENT, SAFETY PLANNING, OPTIMIZATION

In this chapter, the developed systems for scaffolding placement, safety checking and optimization are tested in a case study for validity of the approach. Based on a real-world construction plan, the case study was designed and validated. Construction managers of the project participated in the preparation for the test and validation of the results.

8.1 Case study introduction

Systems developed throughout this thesis was tested in a five-story campus residential building construction project. BIM, construction schedules, and work sequences were used as the input for the developed systems for scaffolding placement, safety checking, and optimization. The project comprises constructions of three parts: Building A, Building B, and Building C (Figure 59).

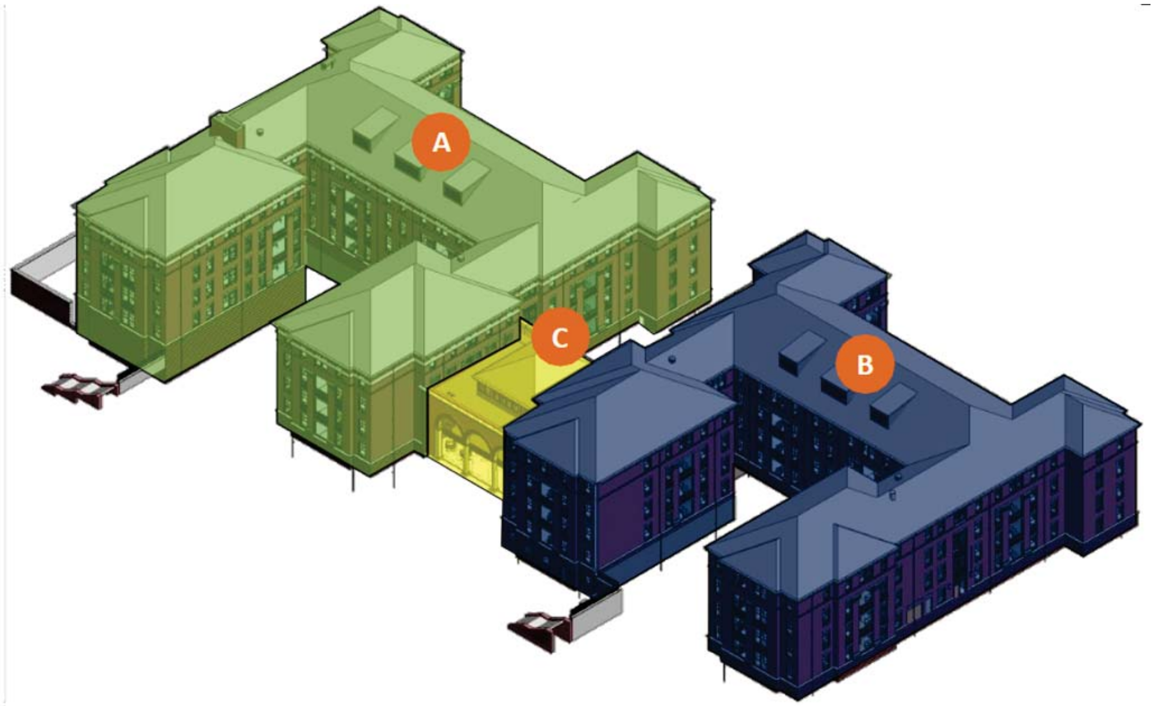


Figure 59: Building model of five-story campus residential building

Figure 60 and Figure 61 present the original construction sequence plans established by the general contractor. Figure Figure 60 shows the construction sequences for structural parts, such as slabs, columns, roofs, etc. In general, Building A is constructed first and then Building B and Building C follow. Building A and Building B have two work zones and Building C has one work zone. Red arrows present the workflows within the work zones. For each floor, work zones and work flows are equally assigned.

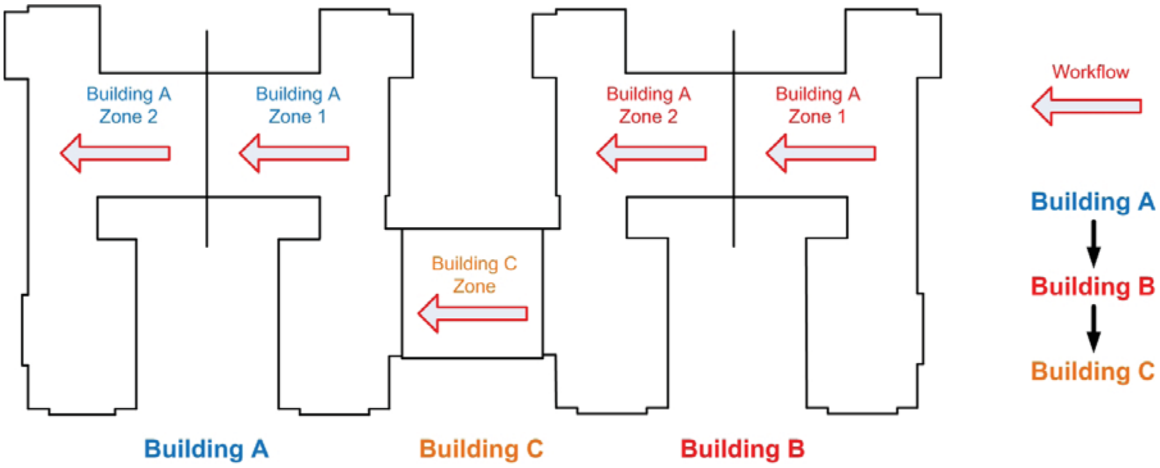


Figure 60: Original construction sequences for structural parts

In addition to the structural part construction, building skin construction sequences were created by the general contractor as shown in Figure 61. Building skin construction is completed by nine sequential tasks including (1) hang exterior sheathing, (2) install fluid applied waterproofing, (3) waterproofing at punched openings, (4) install cornice framing, (5) install Windows, (6) caulk window to waterproofing, (7) stucco at cornice, (8) install brick masonry, and (9) caulk Exterior of Windows. Estimated productivities per crew for the tasks are: (1) hang exterior sheathing (640 sqft/day), (2) install fluid applied waterproofing (640 sqft/day), (3) waterproofing at punched openings (640 sqft/day), (4) install cornice framing (1160 sqft/day), (5) install Windows (1450 sqft/day), (6) caulk window to waterproofing (2890 sqft/day), (7) stucco at cornice (1100 sqft/day), (8) install brick masonry (300 sqft/day), and (9) caulk Exterior of Windows (1450 sqft/day). To assist in the tasks of skin construction, all required mast climber scaffolds were installed and maintained until the entire exterior finishing was completed. Figure Figure 61 presents the general contractors plan for skin construction. Each of the yellow line segments presents a location of a scaffolding installed in front of the building skin. As shown in red arrows, two crews were assigned to each Building A and Building B. Skin construction of Building C was conducted by another crew independently from Building A and Building B.

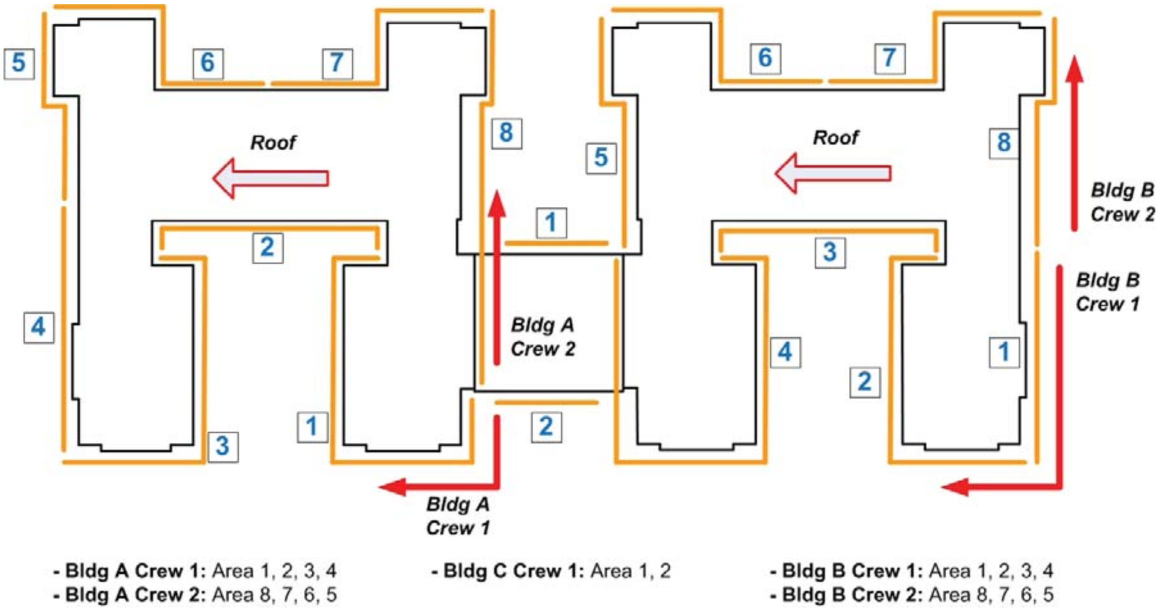


Figure 61: Sequence for building skin construction

8.2 System preparation for simulation and optimization

8.2.1 4D BIM preparation

Based on the original construction plan and BIM of the general contractor, the simulation and optimization were prepared. As the first step, 4D BIM was constructed by linking tasks in a construction schedule and building components, such as walls and slabs. As shown in Figure 62, location lines for scaffoldings were manually created according to the general contractors skin construction plan. The scaffolding location lines were also linked to tasks of skin construction. The location lines were used as the essential input to automatically generate scaffolding objects. To ensure the simulation to properly present the planned construction sequences, constructed 4D BIM has been revised based on the review by the construction managers.

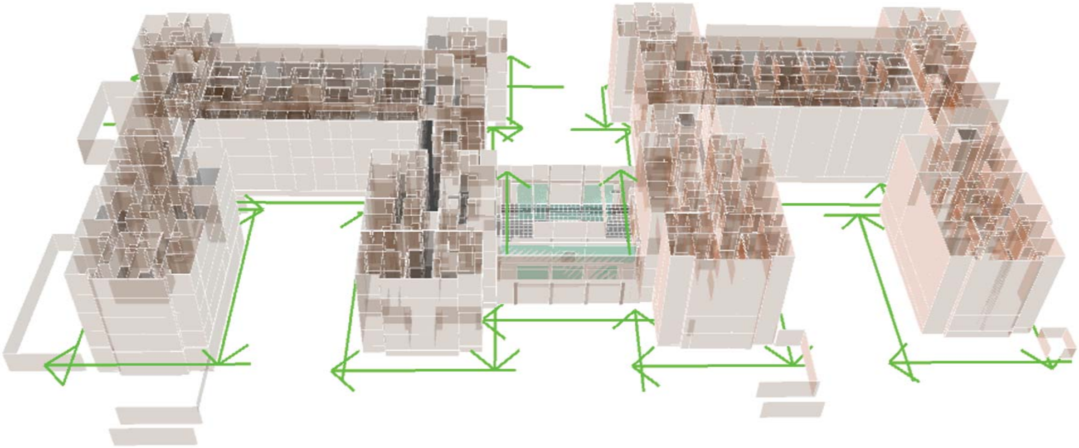


Figure 62: Scaffolding location line input

Also, the system has been refined to meet the need for simulating construction site conditions in finer details. The work zones of the original construction plan were created in the system as shown in Figure 63. Since large sizes of work zones could not properly represent the movements of work crews, each work zones was automatically divided into four sub-work zones (Figure 64).

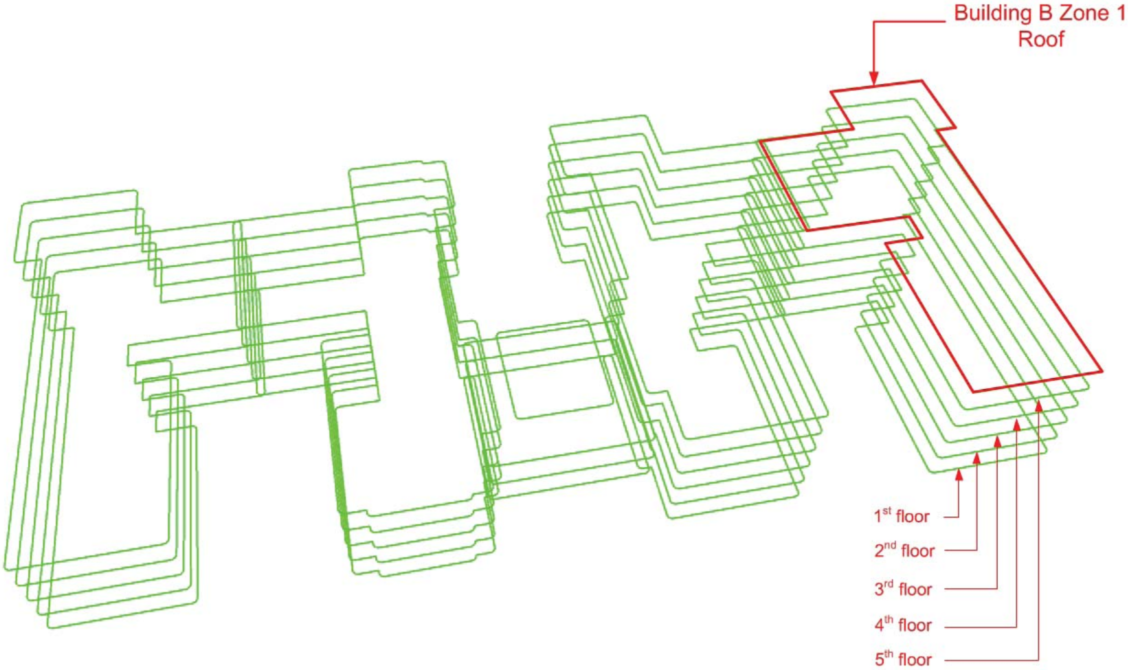


Figure 63: Work zones specified in the original construction plan

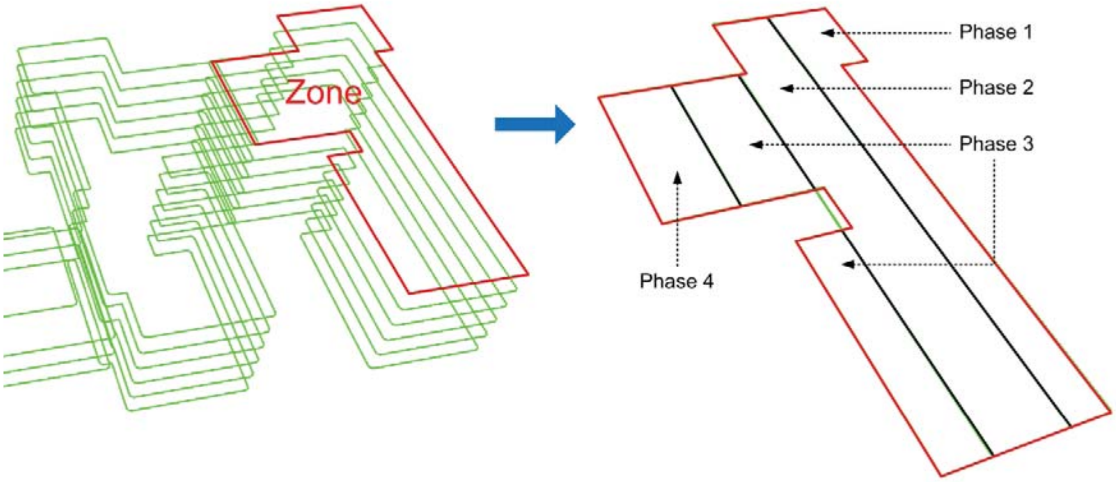


Figure 64: Partitioning of work zones for the safety simulation

8.2.2 Optimization input preparation

After 4D BIM has been constructed, the input for optimization was prepared. Optimization input preparation was conducted by defining multiple options for the decisions made for the original scaffolding plan. The input types included scaffolding size, number of crews per building, skin task order switch, skin task path switch, and structural part work sequence switch. Details are explained below.

1. Scaffolding sizes

   The scaffolding size option limits the width of individual scaffolds by splitting the scaffolds of widths greater than a predefined maximum width. This option has been prepared to allow more crews to work at different levels at the same time. As shown in Figure 65, two scaffolding objects can be created instead of one scaffolding as planned in the original skin construction plan. If additional mast climbers are installed, greater expense is expected due to installation and maintenance of electric-powered lifting units. Related cost calculation is included in the objective function. There are two (true and false) alternatives related to this options.

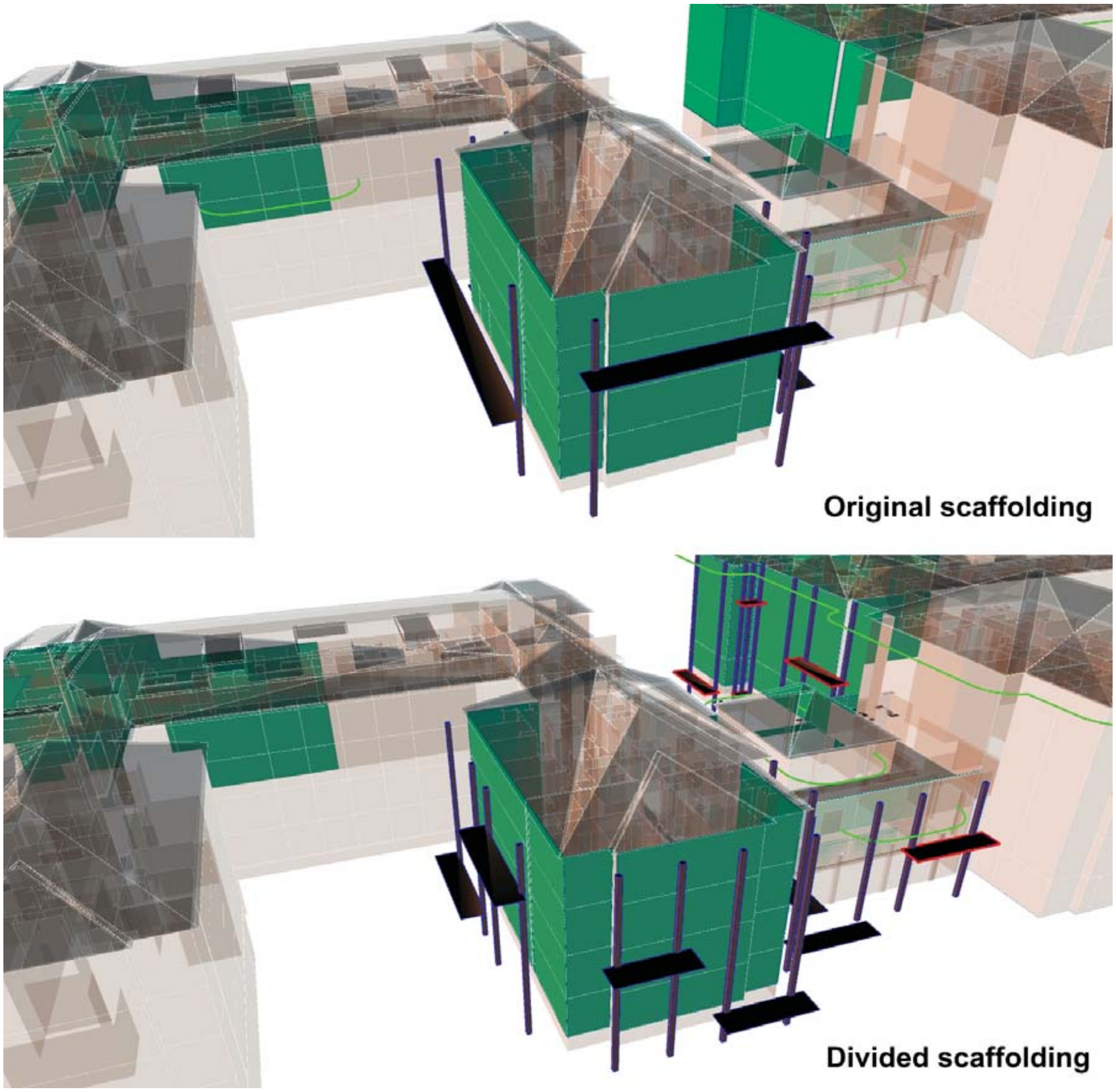


Figure 65: Scaffolding placement with width limitation

2. Number of crews per building

   This option changes the number of crews for skin construction for each Building A and Building B. In the original skin construction plan, there are two crews for each building. This option allows simulations based on one-crew and two-crew assumptions. Figure 66 illustrates work sequences when one crew is assigned to a building. There are two (one and two) alternatives related to this options.

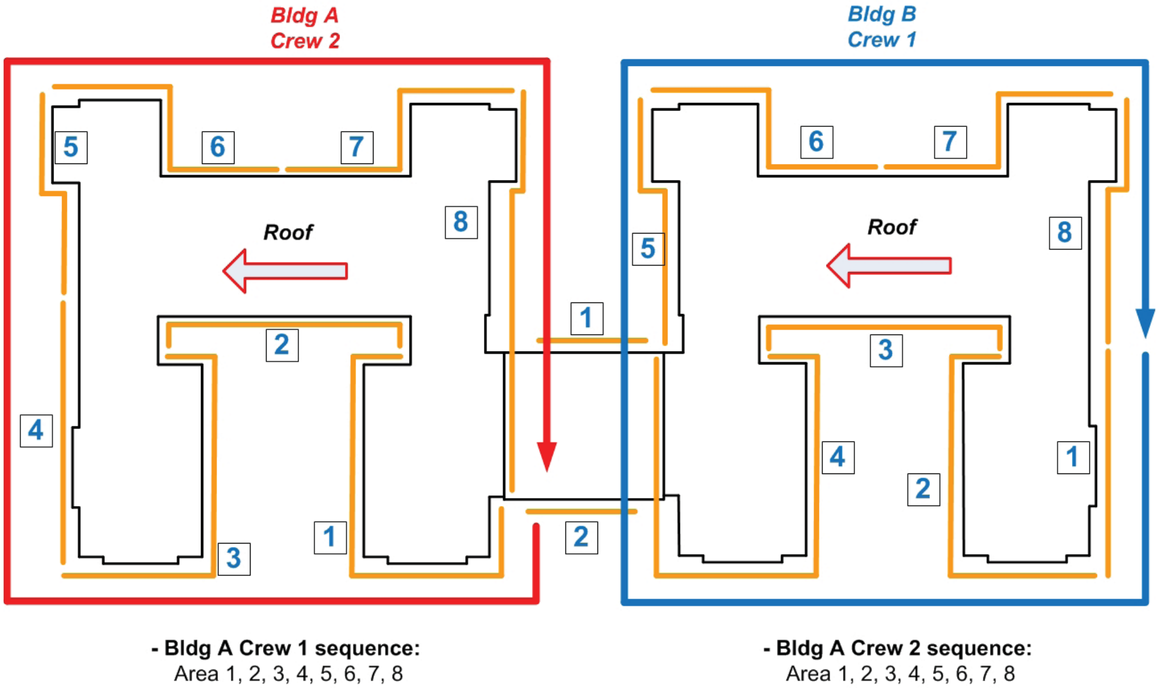


Figure 66: Sequences for one crew for Building A and Building B option

3. Skin task order switch

   Skin task order switch is to reverse the sequence of skin construction tasks. As illustrated in Figure 67, there are eight skin construction tasks for each Building A and Building B. The original sequence for crew 1 of Building A is 1, 2, 3, and 4. After reversing the sequence, construction is conducted following the reversed order which is 4, 3, 2, and 1. There are two (true and false) alternatives related to this options.

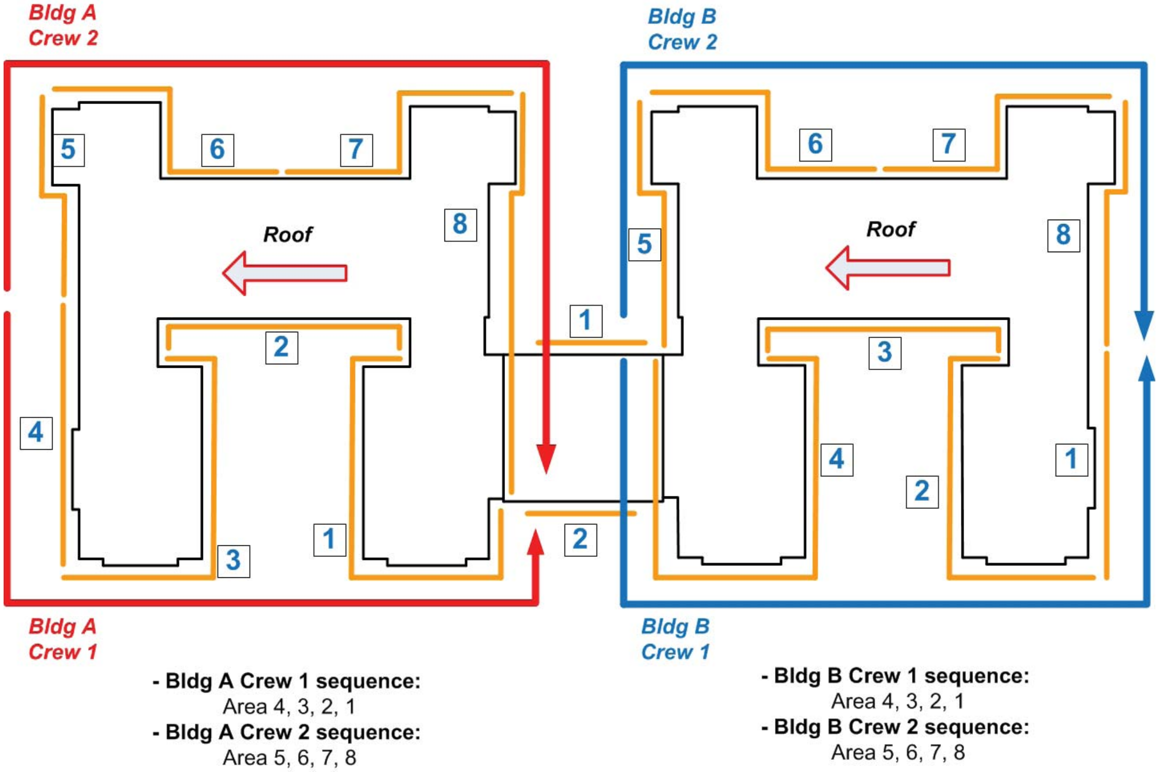


Figure 67: Reversed task order option

4. Skin task path switch

   Task path switch option determines if a work direction in a task follows the preplanned sequence or if the sequence is reversed. If a task is linked to only one scaffolding object, this option does not make any change. However, the work direction changes if a task has two or more scaffolding objects. Figure 68 compares the work directions when the order was switch and not switched. There are four (true and false for Building A and Building B) alternatives related to this options.

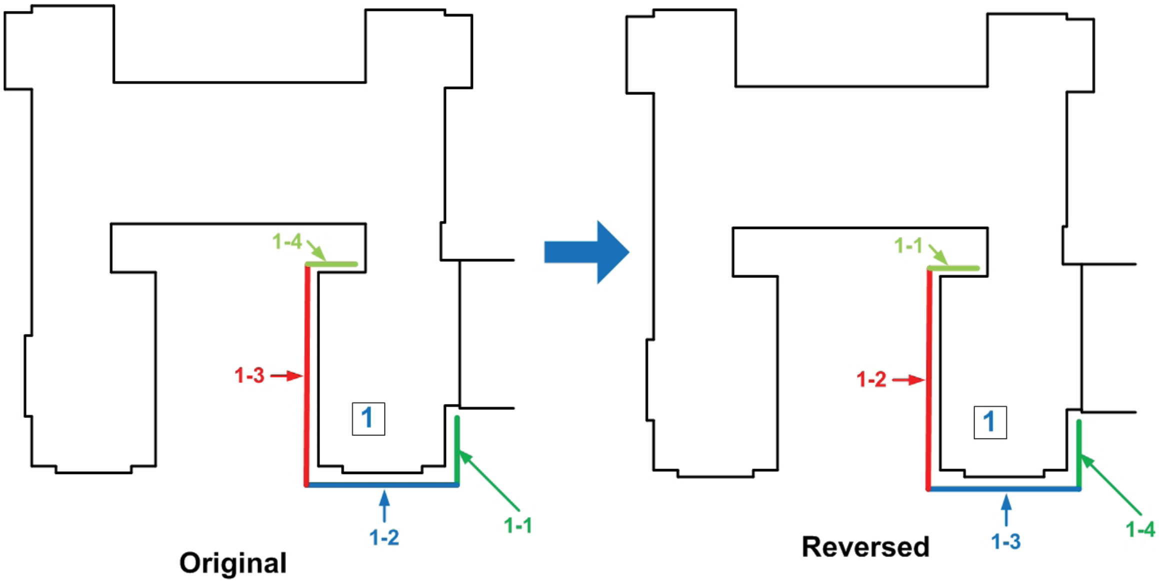


Figure 68: Reversed paths in a task

5. Structural part work sequence switch

   This reverses the work directions of structural part construction in a building. Since there are three buildings (Building A, Building B, and Building C), each of them can be reversed as shown in Figure 69. There are eight (true and false for three buildings) alternatives related to this options.

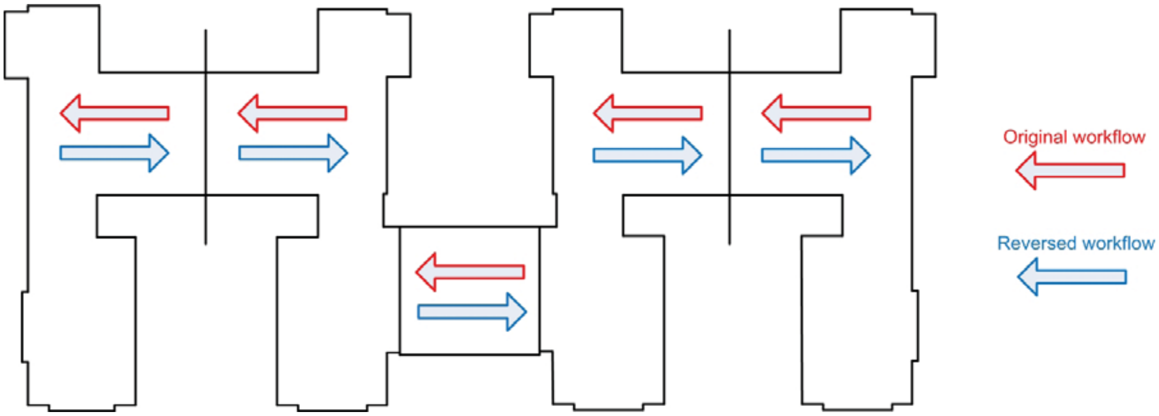


Figure 69: Reversed structural sequences

As a result of enumerating all the combinations, 256 total alternatives were automatically generated.

8.2.3 Objective functions

Objective functions are required to quantitatively evaluate each scaffolding alternative. In addition to safety hazards, the total duration for skin construction and the total cost for scaffolding were calculated to provide an insight into performances of alternatives. The objective functions have been created based on a discussion with construction and safety managers of the project. Even though simplistic methods were used for this case study, more realistic calculations of subcontractors can be integrated into the system.

1. Safety hazard score

   Safety hazard score was calculated by multiplying weights to identified safety hazards and summing the results for all safety hazards identified by the system. The maximum score for an incident was 10 and the minimum score was 0. Two types of safety hazards were checked by the system: falling objects from scaffolding and falling objects to scaffolding. Table 3 shows the objective functions for each task of skin construction. There is no activity occurring at the locations where scaffolds are installed and all there is no additional scaffolding installation once the skin construction starts. Therefore, other types of scaffolding-related safety hazards, such as spatial conflicts with other tasks, falling objects to scaffolding installation spaces, were not included in this case study.

Table 3: Safety hazard score calculation functions

Hazard type	Task	Objective function
Falling objects from scaffolding	1. Hang Exterior sheathing	1 per incident
	2. Install Fluid Applied Waterproofing	0 per incident, only visualization
	3. Waterproofing at Punched Openings	0 per incident, only visualization
	4. Install Cornice Framing	1 per incident
	5. Install Windows	$(\text{Falling distance} \div 20) \times 4, \text{maximum } 4$
	6. Caulk Window to Waterproofing	1 per incident
	7. Stucco at Cornice	1 per incident
	8. Install brick	$(\text{Falling distance} \div 20) \times 10, \text{maximum } 10$
	9. Caulk Exterior of Windows	0 per incident, only visualization
Falling objects to scaffolding	Any falling objects to scaffolding	$(\text{Falling distance} \div 20) \times 10, \text{maximum } 10$

2. Total duration for skin construction

   The total duration required to complete the entire skin construction is calculated at the end of the simulation of each alternative.

3. Total cost for scaffolding installation and maintenance

   The total cost for scaffolding installation and maintenance was calculated based on a simplified method. The cost depends on the total duration for skin construction and the number of masts that need electric power for vertical movement. All the mast climbers were installation and then dissembled after the entire skin construction was completed. The objective function for scaffolding cost is shown below.

$$\text{Scaffolding cost} = \text{Utilization and maintenance} + \text{Electrical mast}$$

$$\text{General utilization and maintenance} = \text{Skin construction duration} \times \$180$$

$$\text{Electrical mast installation and maintenance} = \$10{,}000 \text{ per mast}$$

8.3 Implementation results

The performance of the system was evaluated for scaffolding placement, potential safety hazard recognition, and optimization of the original scaffolding plan.

8.3.1 Scaffolding placement

Based on the information in BIM and user input, the system successfully created scaffolding objects in 4D BIM environment. Figure 70 illustrates the result of plane-face intersection analysis. The intersection analysis identified bottom and top points along the work package and determines the shapes of scaffolding objects. Scaffolding objects and workspaces for structural construction tasks were created and incorporated into 4D BIM as shown in Figure 71.

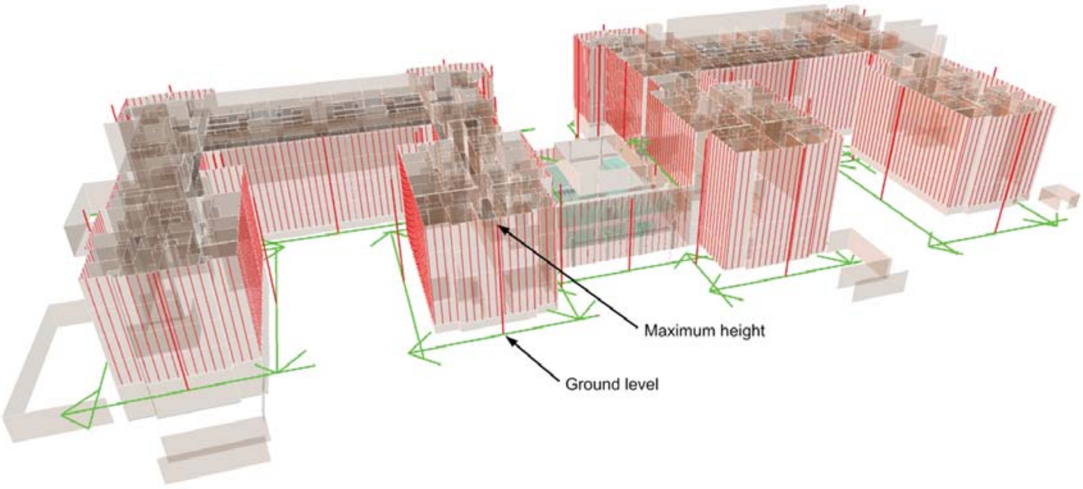


Figure 70: Result of plane-face intersection analysis

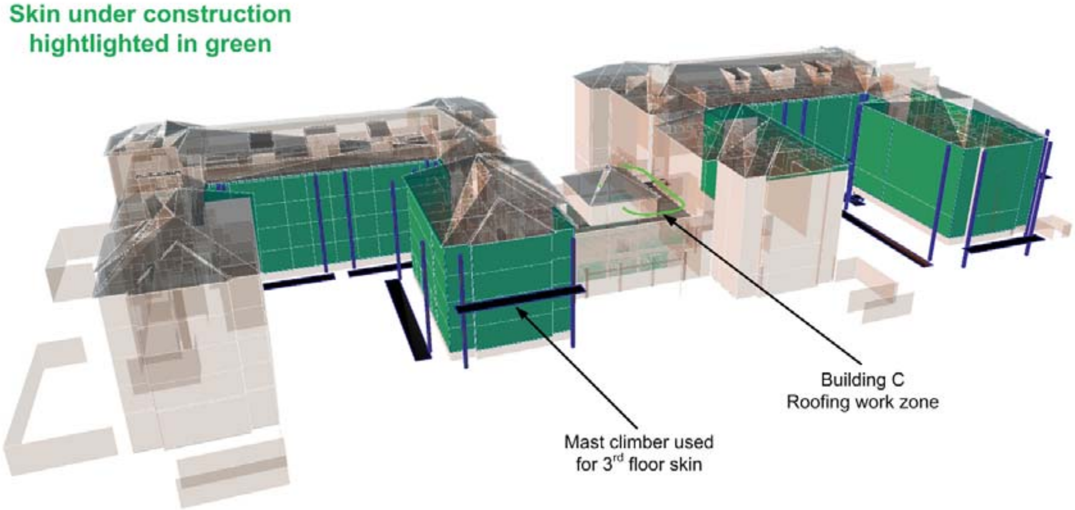
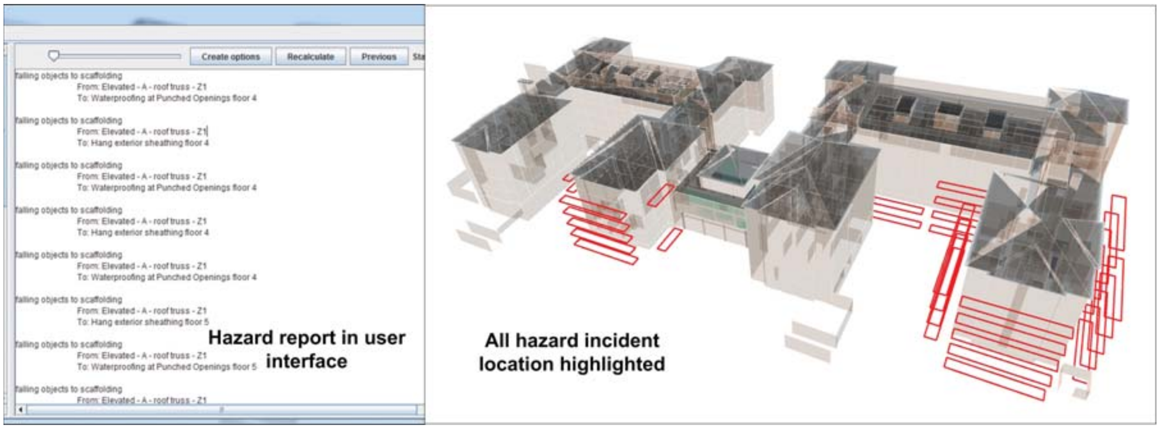


Figure 71: Mast climber scaffolding and structural work zones in 4D BIM

8.3.2 Scaffolding-related hazard recognition

The scaffolding objects were used to identify potential safety hazard and each of the safety hazard incidents was quantitatively assessed based on the objective functions. Figure 72 shows the report and visualization for all safety hazard incidents identified by the system. The hazard report available in the graphical user interface provide detailed hazard information, such as hazard types, dates, and related construction tasks. In the 4D BIM environment, locations for detected safety hazards were visualized to facilitate effective communication about the detected hazards.



```
falling objects to scaffolding
                From: Elevated - A - roof truss - Z1
                To: Waterproofing at Punched Openings floor 4

falling objects to scaffolding
                From: Elevated - A - roof truss - Z1
                To: Hang exterior sheathing floor 4

falling objects to scaffolding
                From: Elevated - A - roof truss - Z1
                To: Waterproofing at Punched Openings floor 4

falling objects to scaffolding
                From: Elevated - A - roof truss - Z1
                To: Hang exterior sheathing floor 4

falling objects to scaffolding
                From: Elevated - A - roof truss - Z1
                To: Waterproofing at Punched Openings floor 4

falling objects to scaffolding
                From: Elevated - A - roof truss - Z1
                To: Hang exterior sheathing floor 5

falling objects to scaffolding
                From: Elevated - A - roof truss - Z1
                To: Waterproofing at Punched Openings floor 5

falling objects to scaffolding
                From: Elevated - A - roof truss - Z1
```

Figure 72: Report and visualization of entire safety hazards

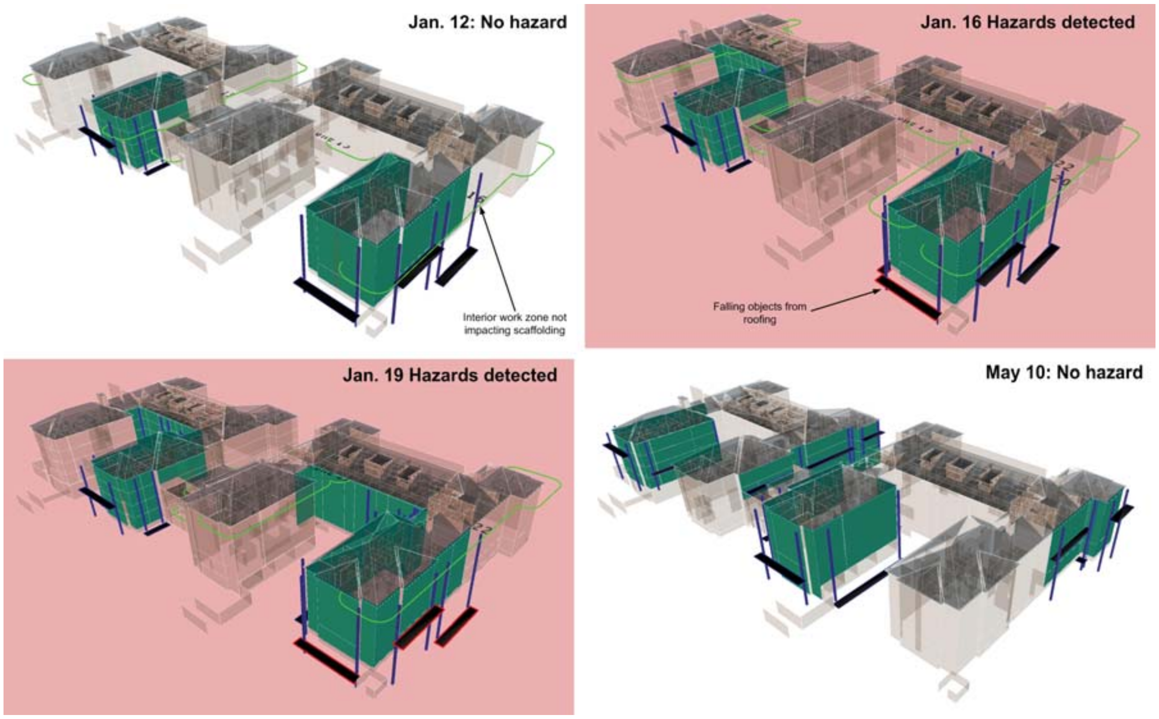
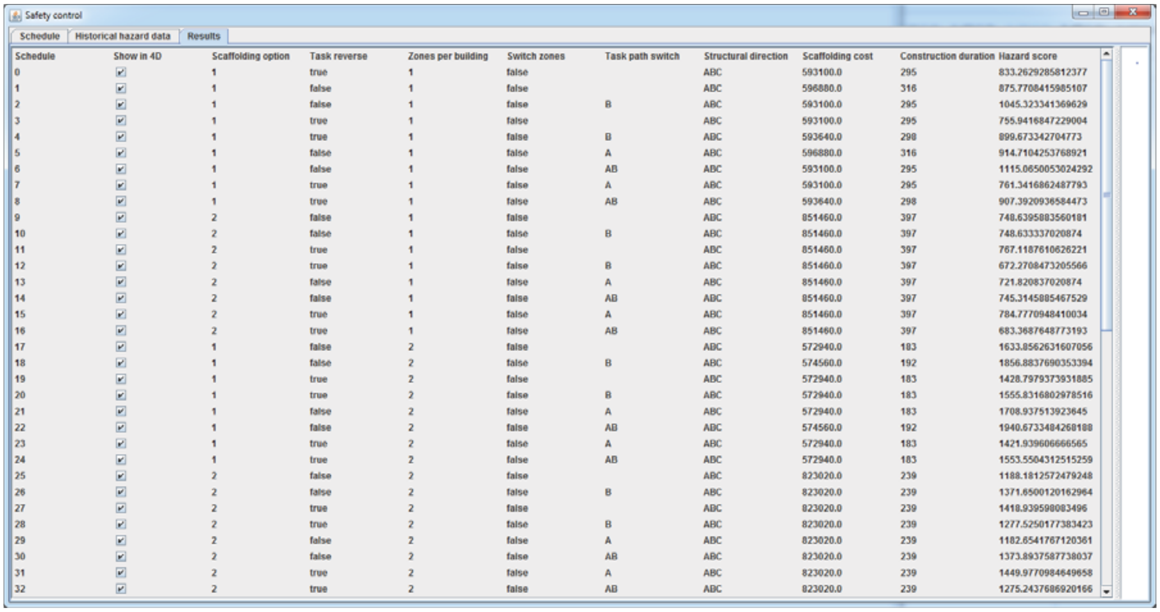


Figure 73: Hazard visualization in 4D environment

In the 4D environment of the system, construction site conditions can be visualized more realistically by incorporating scaffolding objects, workspaces, and safety hazards (Figure 73).

8.3.3 Enumerative generation of scaffolding plan alternatives

Based on the optimization input, all possible alternative scaffolding plans were created and quantitatively evaluated. For each alternative, the safety simulation system analyzed daily construction site conditions and evaluated the plans according to the objective functions. As shown in Figure 74, the scaffolding plans were summarized in the graphic user interface.



Schedule	Show in 4D	Scaffolding option	Task reverse	Zones per building	Switch zones	Task path switch	Structural direction	Scaffolding cost	Construction duration	Hazard score
0	☑	1	true	1	false		ABC	593100.0	295	833.2629285812377
1	☑	1	false	1	false		ABC	596880.0	316	875.7708415985107
2	☑	1	false	1	false	B	ABC	593100.0	295	1045.323341369629
3	☑	1	true	1	false		ABC	593100.0	295	755.9416847229004
4	☑	1	true	1	false	B	ABC	593640.0	298	899.673342704773
5	☑	1	false	1	false	A	ABC	596880.0	316	914.7104253768921
6	☑	1	false	1	false	AB	ABC	593100.0	295	1115.0650053024292
7	☑	1	true	1	false	A	ABC	593100.0	295	761.3416862487793
8	☑	1	true	1	false	AB	ABC	593640.0	298	907.3920936584473
9	☑	2	false	1	false		ABC	851460.0	397	748.6395883560181
10	☑	2	false	1	false	B	ABC	851460.0	397	748.633337020874
11	☑	2	true	1	false		ABC	851460.0	397	767.1187610626221
12	☑	2	true	1	false	B	ABC	851460.0	397	672.2708473205566
13	☑	2	false	1	false	A	ABC	851460.0	397	721.820837020874
14	☑	2	false	1	false	AB	ABC	851460.0	397	745.3145885467529
15	☑	2	true	1	false	A	ABC	851460.0	397	784.7770948410034
16	☑	2	true	1	false	AB	ABC	851460.0	397	683.3687648773193
17	☑	1	false	2	false		ABC	572940.0	183	1633.8562631607056
18	☑	1	false	2	false	B	ABC	574560.0	192	1856.8837690353394
19	☑	1	true	2	false		ABC	572940.0	183	1428.7979373931885
20	☑	1	true	2	false	B	ABC	572940.0	183	1555.8316802978516
21	☑	1	false	2	false	A	ABC	572940.0	183	1708.937513923645
22	☑	1	false	2	false	AB	ABC	574560.0	192	1940.6733484268188
23	☑	1	true	2	false	A	ABC	572940.0	183	1421.939606666565
24	☑	1	true	2	false	AB	ABC	572940.0	183	1553.5504312515259
25	☑	2	false	2	false		ABC	823020.0	239	1188.1812572479248
26	☑	2	false	2	false	B	ABC	823020.0	239	1371.6500120162964
27	☑	2	true	2	false		ABC	823020.0	239	1418.939598083496
28	☑	2	true	2	false	B	ABC	823020.0	239	1277.5250177383423
29	☑	2	false	2	false	A	ABC	823020.0	239	1182.6541767120361
30	☑	2	false	2	false	AB	ABC	823020.0	239	1373.8937587738037
31	☑	2	true	2	false	A	ABC	823020.0	239	1449.9770984649658
32	☑	2	true	2	false	AB	ABC	823020.0	239	1275.2437686920166

Figure 74: Graphic user interface of optimization

8.3.4 Performance-based selection and review in 4D BIM

The quantitative evaluations of the alternatives were used to select a few candidate plans to be reviewed thoroughly in the 4D BIM environment. To provide a clear insight into the expected performances of the alternatives, three ways of result visualization were used. (1) First, 2D and 3D scatterplots were used to select candidates as shown in Figure 75. Five alternatives were selected based mainly on the tradeoff between skin construction duration and hazard score was presented. From the five alternatives, alternative 5 was excluded from further review due to excessively long skin construction duration. (2) For other four alternatives, summary reports were presented to construction managers of the general contractor to assist in their decision making (Figure 77 and Figure 79). (3) Finally, 4D simulation was used to review the four alternatives and make the final decision.

In general, all four alternatives were considered as safer plans that can be actually implemented without significant constructability problems. Also, skin construction can be extended up to 300 days that allows alternative 4 to be a qualified option.

1. Alternative 1, 2: Expected skin construction durations and scaffolding costs of alternative 1 and 2 were almost identical to those of the original plan. Even though the hazard scores were slightly lower, alternative 1 and 2 were not considered as the preferred plans since the work sequence of original plan was simple and easier to implement.

2. Alternative 3: Alternative 3 required about 50 more days to complete the skin construction and needed excessive cost for scaffolding installation and maintenance due to more electric-powered lifting units needed. However, this alternative was selected as one of preferred solutions due to its clear benefit in safety.

3. Alternative 4: Alternative 4 was also selected as a preferred solution even with a duration more than 100 days longer than the original plan. Construction managers opinion was that this plan exposes workers to significantly lower level of safety risks compared to the original plan.

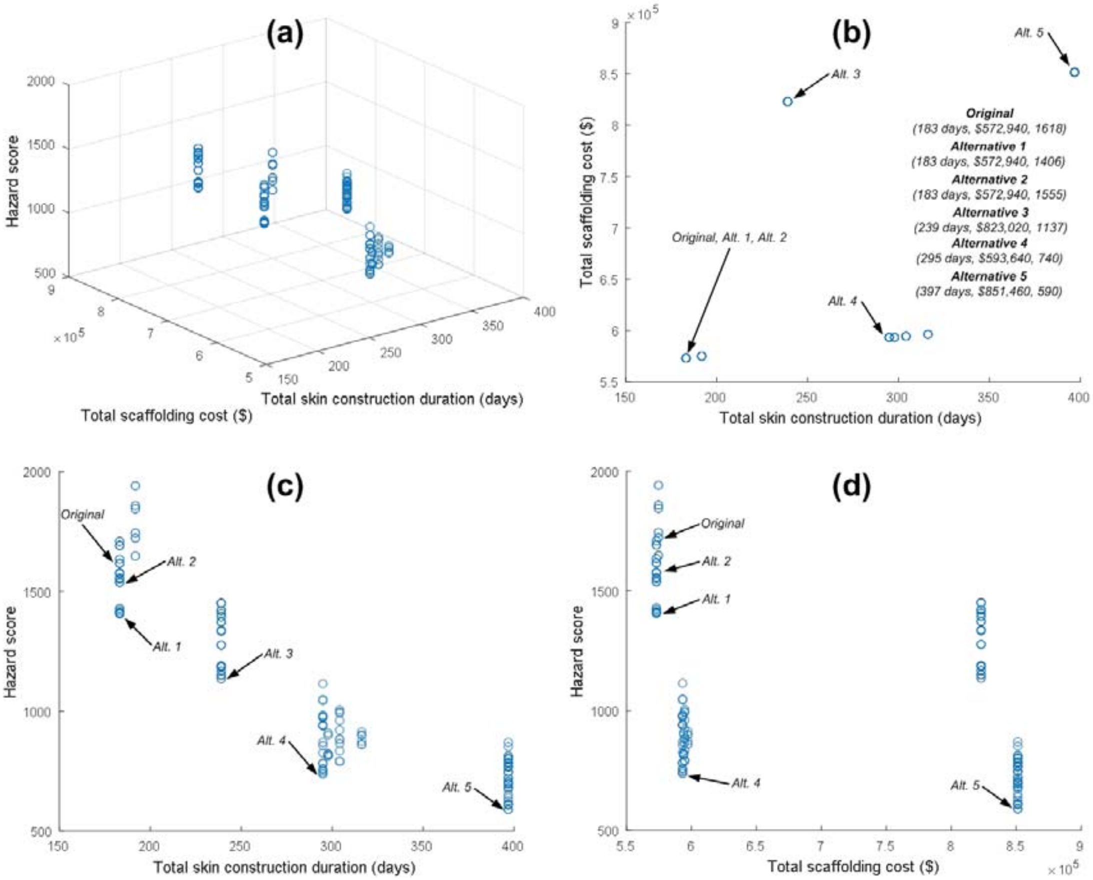


Figure 75: Five alternative scaffolding plans were selected based on the performances

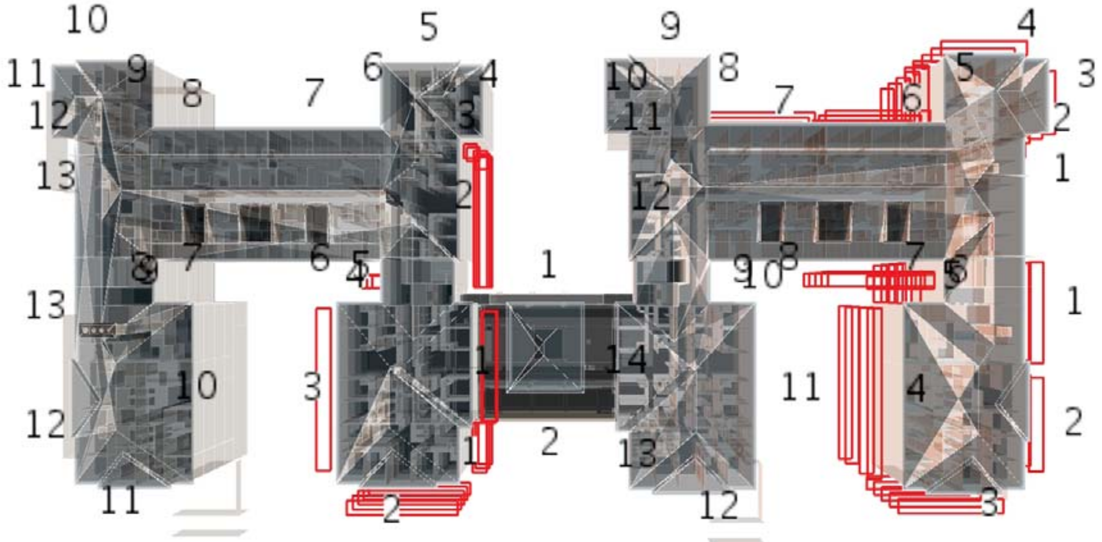
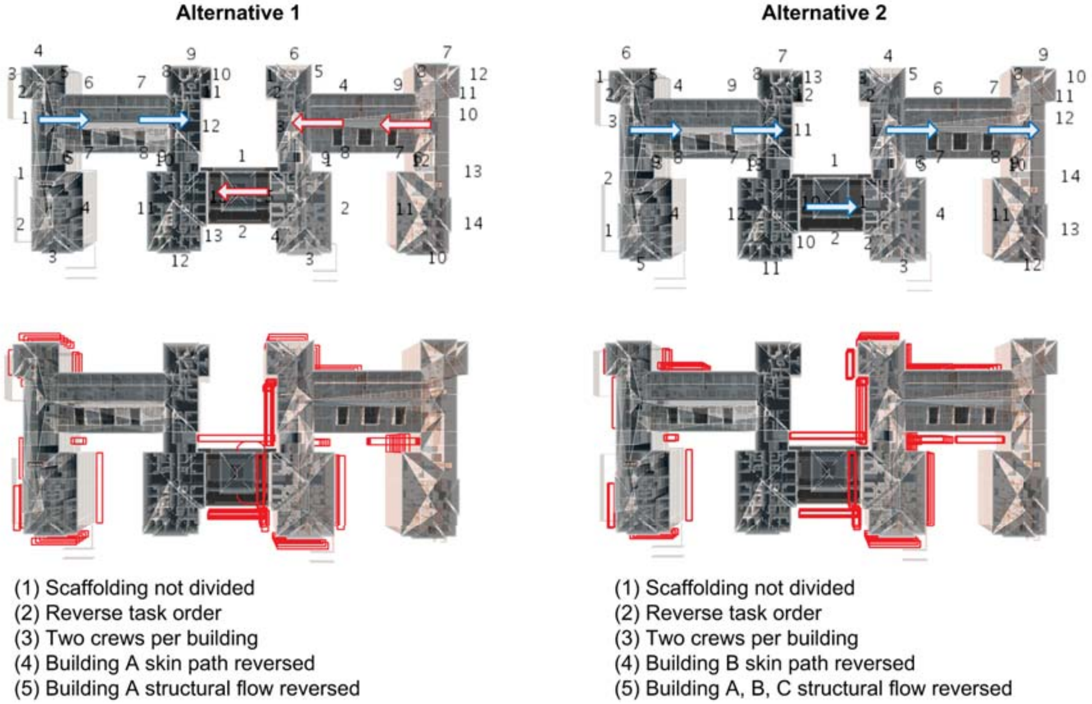


Figure 76: Sequence and safety hazard highlights of original plan



(1) Scaffolding not divided
(2) Reverse task order
(3) Two crews per building
(4) Building A skin path reversed
(5) Building A structural flow reversed

(1) Scaffolding not divided
(2) Reverse task order
(3) Two crews per building
(4) Building B skin path reversed
(5) Building A, B, C structural flow reversed

Figure 77: Scaffolding plan summary for alternative 1 and 2

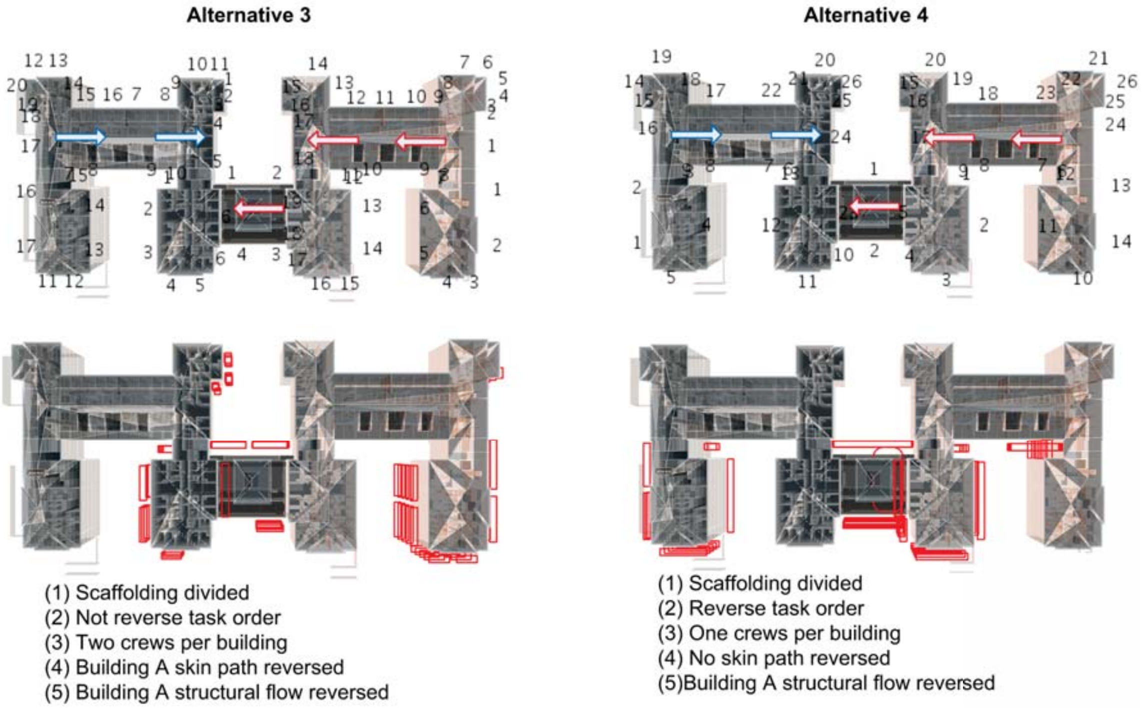


Figure 78: Scaffolding plan summary for alternative 3 and 4

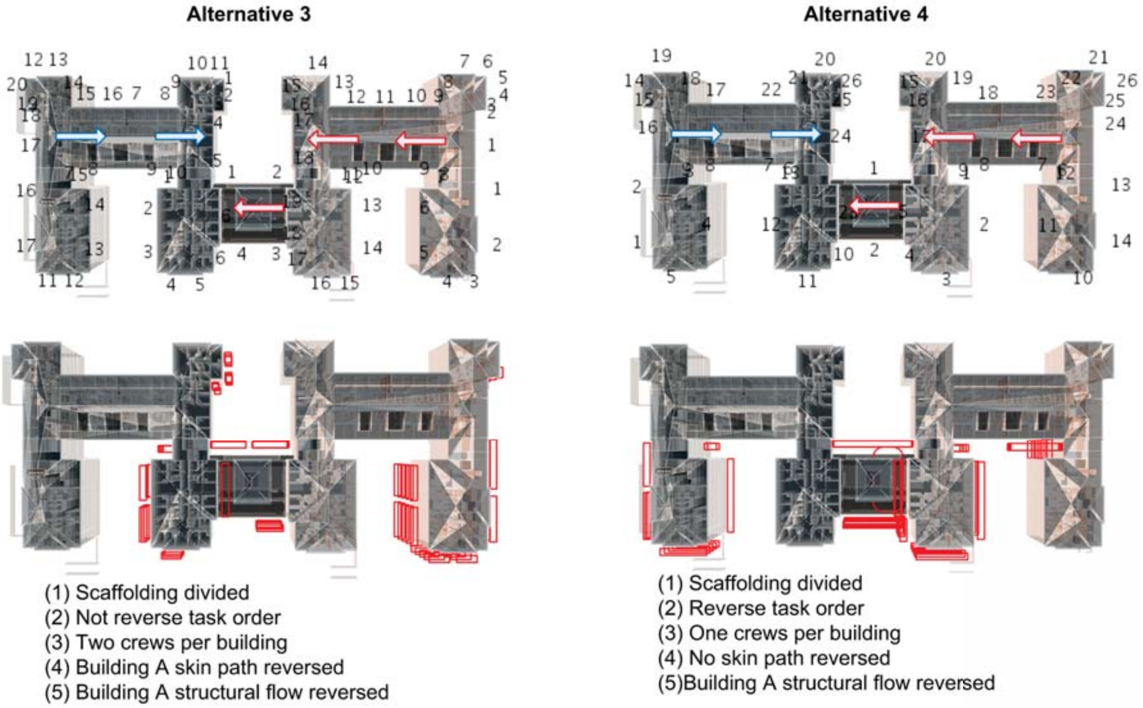


Figure 79: Scaffolding plan summary for alternative 3 and 4

8.3.5 Selection of final scaffolding plan

Alternative 3 and 4 were considered as scaffolding plans that show clear benefits over the original plan. Safety risks associated with alternative 1 and 2 were not considered significantly lower than the original plan. Even with significantly lower level of safety risk of alternative 5, the expected duration for skin construction was excessively longer than the original plan. Thus, the original plan, alternative 3, and alternative 4 were selected as optimal solutions.

8.4 Conclusions and discussion

In this chapter, the overall approach including scaffolding placement, safety simulation, and optimization was tested in a real-world case study. The construction project information in BIM, construction schedules, and sequences were used as the input for the system. Construction managers of the project participated in the entire process of validation, from 4D BIM creation to assessment of the results of simulation and optimization. In the optimization process, a wide range of scaffolding plans were automatically created based on user input and the construction managers actively participated in the selection process. In addition to the quantitative evaluation of alternatives, professional judgment of the construction managers were used to evaluate the constructability and effectiveness of the plans. As a result, multiple alternative scaffolding plans were identified that were considered safer than the original plan. Thus, this case study validates that manually generated original plan for temporary structures can be evaluated and optimized into safer temporary structure plans by the proposed automation approach.

The limitations of this case study include: (1) Hazard weighting required multiple rounds of adjustments. Since experts participated in the test had different opinions about the risks of safety hazards, discussions were required to setup the hazard weighting. (2) Other user-input, such as reversing sequences and directions, also required multiple adjustments based on preliminary 4D reviews of construction managers. (3) Performance-based selection needs an additional function to select alternatives based on certain criteria. In this case study, five alternatives were selected mainly based on skin construction durations and hazard scores. For example, creating functions to select alternatives with hazard score lower than 500 and one crew per building can be helpful in reducing the need for manual efforts for selection and review.

Real-world application of this approach expected to be achieved by overcoming these limitations.

CHAPTER IX

CONCLUSIONS AND LIMITATIONS

This chapter summarizes the findings and concludes the thesis. Limitations of the current reserach and future research needs are discussed.

9.1 Summary of works performed

This research presents a BIM-based automatic system to address potential safety hazards related to temporary structures in the planning stage. Focusing on scaffolding, this research attempts to improve the construction safety by (1) automatically incorporating temporary structure objects in a 4D BIM, (2) automatically identifying potential safety hazard incidents related to the temporary structures, and (3) optimizing the original temporary structure plans into safer scaffolding plans.

As the first step, a process for scaffolding planning was established based on in-depth interviews with industry professionals. The scaffolding placement process was then converted into a set of computational algorithms. Scaffolding objects were automatically created in 4D BIM by analyzing spatial-temporal condition in BIM.

The BIM containing scaffolding objects were used to identify potential safety hazards related to scaffolding. To enable an automated hazard identification, a safety simulation engine was developed. The safety simulation engine created daily requirements for workspaces and scaffolding objects to accurately analyze construction sites on each day. The safety simulation engine demonstrated its capabilitiy to identify potential safety hazards without excessive manual efforts and to effectively communicate the results.

The scaffolding optimization is create optimized scaffolding plans that are safe and executable. This optimization has been accomplished by automatically creating alternative scaffolding plans and quantatively evaluating them. Quantitatively evaluated performances of scaffolding plans assisted in construction planners to make informed decision making based on the predicted performances on safety and other criteria, such as cost and duration.

The proposed approach for scaffolding planning, analysis, and optimization was validated in another real-world construction project. Construction and safety managers of the case study project actively participated in the process from preparation of the simulation to the validation of the final results. In this case study, scaffolding objects were successfully created in a 4D BIM environment and potential safety hazards were automatically identified. Based on the user-input, alternative scaffolding plans were automatically created and evaluated. Finally, the construction managers selected a few alternatives based on the expected performances. As a result of reviewing the selected alternatives, multiple alternative scaffolding plans were found to be executable and safer than the original scaffolding plan.

9.2 Contributions and impacts

The major contributions and impacts of this reseach are presented. (1) The first contribution of this reserach would be that safe temporary structure plans can be created without excessive manual efforts. Time-consuming and error-prone tasks of identifying and addressing temporary structure-related safety hazards were automatically conducted in this research. (2) Construction site safety can be improved by recognizing and addressing potential hazards related to temporary structures before the construction begins. The overall approach proposed in this research can assist construction and safety planners in preparing preventive actions in the planning stages. (3) A wide range of possibilities to plan temporary structures can be explored to assist in the informed decision making. A method for automated generation of temporary structure plan alternatives and quantitative assessment of the alternatives was proposed. Through the enumerative generation of alternative plans and quantitative evaluation, construction planners can have a clearer insight into possible ways of planning temporary structures. (4) Safety communications can be facilitated using hazard schedules, hazard-specific reports, and hazard visualization. Various hazard visualization methods presented in this research can greatly improve safety communications between superintendents, safety managers, inspectors, and workers. (5) Better safety training can be provided to workers through hazard visualization and reports. (6) Workers can obtain ease-of-mind by clearly recognizing potential hazards around them. All these eventually contribute to the creation of safe construction plans that minimize worker exposures to safety hazards.

9.3 Limitations and future research

One of the fundamental limitations of this research is the heavy reliance on the accuracy of geometric information in BIM and construction schedules. If the project information is incorrect, the temporary structure planning is directly impacted. This requires BIM and construction schedules to be continuously updated to contain accurate geometric and non-geometric information. The performance of the approach can also be impacted by the level of details and quality of 4D BIM and construction schedules because it attempts to simulate daily construction site conditions.

The current research dealt with building models with relatively simple geometric conditions. Planar faces of walls, slabs, and roofs were used for automated construction site conditions analysis. In order to develop a practical application software program, the geometric condition analysis algorithms need to be able to analyze various types of geometry such as curved walls.

Development of algorithms in this research focused on selected construction tasks, such as masonry wall construction and building skin construction tasks. Depending on the charatecterstics of tasks, required functions of algorithms can vary widely. In order to overcome this limitation, a comprehensive study to computationally generate work sequences and patterns of tasks using scaffolding is required. Patterns of spatial movement of workers have been studied in the past research studies [36]. Automatically creating various work patterns in BIM and matching the patterns to construction tasks would be one of the solutions to this limitation.

During the optimization process, the selection process can be enhanced by creating selection algorithms and filters. Since hundreds of alternatives were automatically created, it was challenging to review enough number of alternatives manually.

Also, the optimization was conducted by adjusting parameters related to temporary structures. A future research can enable an optimization in the earlier stages when zoning plans and construction schedules are established. By incorporating automated generation and analysis approaches in the earliest stage in constructino planning, wider range of construction planning alternatives can be explored and construction plans can be established based on a clearer insight into possible ways of construction.

Integration of a wider range of temporary structures can be considered in future studies. This research focused mainly on scaffolding. However, for more realistic visualization and analysis, other important temporary structures such as formwork may need to be incorporated. Interactions between different types of temporary structures may also be considerd in the analysis.

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