Using BIM to Automate Scaffolding Planning for Risk Analysis at Construction Sites

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Abstract –

Scaffolding system plays an important role at construction sites. According to the Occupational Safety and Health Administration (OSHA), 65% of the construction workers use scaffolding system frequently. Each year, there are 4500 injuries and 50 deaths caused by scaffold-related accidents, costing American employers $90 million on lost workdays. Thus well conducted risk analysis on scaffolding system can have a significant impact on project performance. Although many governments developed safety regulations and standards for scaffolding system, it is still a challenge for construction safety managers to execute these regulations at construction sites. One of the reasons is that these regulations are documents which require construction safety manager to accurately translate the information with 2-dimentional drawings into a workable safety plan. Building Information Modeling (BIM) has been employed to enhance safety management at construction sites; however, scaffolding system, as a temporary facility, is usually not developed in the BIM model. Consequently, scaffold-related hazards are hard to be identified and analyzed.

This study focuses on constructing a BIM-based scaffolding safety management model to analyze various scaffold-related risks and provide solutions. First, the requirements for scaffolding planning are identified by developing an ontology for risk analysis. Then a series of Dynamo modules are established to automate the process of developing the scaffolding system in the BIM model according to the requirements identified. Next, various simulations based on the potential hazard events are conducted to serve as a tool for educating construction workers and determining solutions. In addition, safety checklists with 3-D location information are derived from the BIM model to help safety managers reduce the difficulties of implementing safety regulations and improve the quality of safety management at construction sites.

Keywords –

BIM; Scaffolding System; Risk Analysis; Ontology; Dynamo

1 Introduction

The scaffolding system is widely used to support construction activities, such as bridge construction and housing. As a temporary structure, it's often omitted from drawings or BIM, therefore the planning of a scaffolding system depends heavily on subcontractor's experiences. Moreover, scaffolding system contains lots of elements, and the way it is built also influences its strength and construction safety. According to the annual report from the Occupational Safety and Health Administration [1], the death toll of the construction industry accounted for almost 50% of all industries, and scaffolding system is the main contributing factor, causing an average of 20 deaths each year.

In order to implement scaffolding checklist items and execute regulations at construction sites by safety manager, this research provides a BIM-based scaffolding system management framework that can reduce fatal damage due to bad scaffolding planning. First, scaffolding system layout, potential hazards and scaffold elements are analyzed by ontology modeling to clarify requirements of the BIM model. Next, according to the results which are analyzed by ontology and the space information provided by BIM model, the development guide of the assembling scaffolding system is established. Finally the Revit plug-in, Dynamo is employed in the automated planning of the scaffolding system for further risk analysis. Using BIM model's advantage of visualization, safety checkpoints can be marked directly on the model. Safety managers can compare the model with the construction site so that checkpoints and hazards can be identified to conduct a complete inspection task in an effective way.

This paper is organized as follows. Related works section presents a review of existing studies on scaffolding system safety management, BIM-based safety management and scaffold planning, and ontology application of the construction phase. The methodology section presents every platform and safety simulation tool used in this research. In the framework section, the flow chart of the research is explained in detail. The last section concludes the research and discusses contributions, limitations, and potential for future studies.

2 Related Works.

2.1 Scaffolding System Safety Management

The scaffolding safety regulations, besides rules set by OSHA (Occupational Safety and Health Administration), Construction safety regulations or standards [2] and Labor Safety and Health Act [3] are also included. Additionally, scaffolding system's material specification, strain requirements and measurements are provided by CNS4750 and CNS4751 [4].

At present, safety inspection of scaffolding system at a construction site is based on a checklist included in the safety devices. The items are listed on forms and checked by the safety manager every day. Although the contents of the checklists vary from stakeholder to stakeholder, the framework and the concept follow rules mentioned in the last paragraph. However, the location needed to be checked is not mentioned on the form and without showing the drawings or BIM model. By analyzing the checklists, the requirements of scaffolding system safety management are established. The objective of this research is to identify ways of improvement in scaffold safety management.

2.2 BIM-Based Safety Management and Scaffold Planning

Traditionally, construction safety management is based on regulations, drawings and a large number of paper-based documents, so the integration of this information has always been a big issue. In 2012, Zhang et al [5] proposed a framework for implementing an automated rule-based safety checking in BIM as shown in Figure 1. The research is based on BIM model elements and it analyzes the risk factors that may be encountered in construction sites, then matches the elements to relevant regulations to establish a framework of applications for BIM in the safety regulatory system.

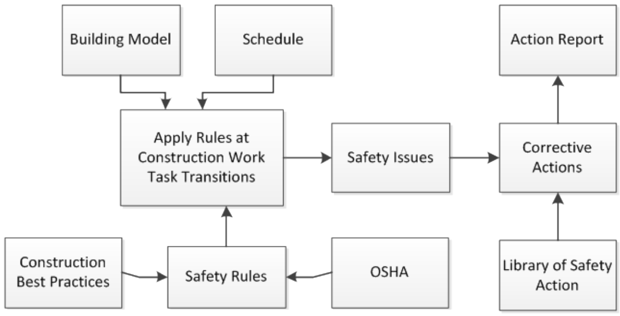

Figure 1. A framework for implementing an automated rule-based safety checking in BIM

Sacks et al. [6] proposed a safety planning system with safety assessment and response measures. The study separates work regions according to construction work item influence, combines with the project schedule and shows the result in the BIM model to improve safety management on site.

On the other hand, the issue of BIM-based scaffolding system, Kim et al. [7] published a rule-based automatic deployment of scaffolding system in the BIM model to improve modeling efficiency by identifying the areas which require scaffolds to be installed and calculating the quantity of the space information from the BIM model. Though the study can plan scaffolding system automatically, it still has a problem if the building is designed with irregular surfaces. Later, Kim [8] also integrated work sequences and temporary structures into safety planning and proposed a framework that automated scaffolding-related safety hazard identification and prevention in BIM. The study mainly focuses on the hazard of falling items during the sequences of the project, but the path calculation depends on the information entered by different subcontractors who use the scaffolding system.

2.3 Ontology Application on Construction Phase

Gruber [10] defined ontology as "an explicit and formal specification of a conceptualization." Ideally, an ontology should (1) capture a shared understanding of a domain of interest and (2) provide a formal and a machine readable model of the domain. The ontology should have the following four characteristics: (1) conceptualization; (2) formal; (3) explicit; (4) share. An ontology framework consists of (1) "class", which describes domain set with familiar properties, and it's made by vocabularies; (2) "attribute" describes properties of every class; (3) "relationship" is used to define all relevance between one another; and (4) "instance" is the specific implementation of class, used to more clearly express the concept.

In 2015, ontology is applied to construction safety management and the framework was proposed by Zhang [11]. Figure 2 shows the system structure of an ontology-based hazard identification application which includes an ontology editor, reasoner, rule engine, and BIM platform.

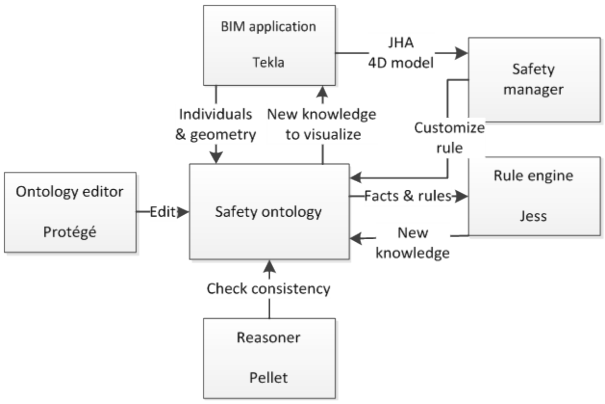

Figure 2. System architecture of the ontology-based hazard identification application in BIM

3 Methodology

The following sections will briefly explain the tool used in this research.

3.1 IDEF0

IDEF0 is used as a project analysis tool which is patterned to describe the production of information, functions and processes of the symbol of the frame, diagrams, activity boxes and arrow, as shown in Figure 3.

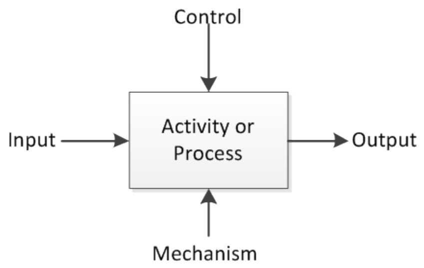

Figure 3. Legend of IDEF0

3.2 BIM Application

3.2.1 Revit 2017

The BIM modeling tool used in this study was Revit 2017 developed by Autodesk. Revit series software has been fully integrated with architecture, structure and MEP since 2014, time can be saved between document transfers during modeling.

3.2.2 Dynamo

Dynamo 1.2.1 is the latest version of the plug-in of Revit. In other words, Dynamo can be driven by clicking the Dynamo button to open the program directly from the Revit interface, and the action we do in Dynamo is directly connected with BIM model. Dynamo is a platform that enables designers to explore visual programming, solve problems, and make their own tools. Designers are able to work within a Visual Programming process by connecting elements together to define the relationships and the sequences of actions that compose custom algorithms. We can use our algorithms for a wide array of applications - from processing data to generating geometry - all in real time and without writing a lick of code [12].

3.3 Ontology Application

3.3.1 Ontology Editor- Protégé

Protégé is an open resource platform used to construct domain models and knowledge-based applications with ontologies. The OWL-based (Ontology Web Language) ontology is modeled and edited using protégé to define its class, relationship, attribute and instance.

3.3.2 SWRL

SWRL, so call Semantic Web Rule Language is a language that is used to express rules as well as logic when combining OWL DL or OWL Lite with a subset of the Rule Markup Language. To build a complete ontology model, it is not enough to solely depend on Protégé. Although reasoner can infer the relationship between main classes and check the consistency and integrity of the ontology model, it is unable to describe instance properties and mathematical logic operations. Those complex inferences are described by SWRL.

3.4 Navisworks

4D simulation is more commonly used by Autodesk Navisworks developed by Autodesk as visualization software. The software can also be used as a 4D construction simulation function in combination with the scheduling information to visualize the entire project process and reduce the occurrence of the construction site conflict or errors and other issues, and clearly, let the contractor understand the entire project implementation process.

4 Framework of Using BIM to Automate Scaffolding Planning for Risk Analysis

The framework of this research is shown in Figure 4. First of all, we integrate all the relevant scaffolding regulations, and obtain the needs of subcontractors and on-site engineer's requirements through interview to define which information should be input into the scaffolding system management model. Then we use the concept of ontology to construct the knowledge model by using the information obtained in the last step, and assign scaffolding elements with properties and write the detailed rules through SWRL rule to build an ontology model with a scaffolding hazard analysis and planning knowledge. Then, according to analytical knowledge in ontology model, the know-how is applied to build a scaffolding system in BIM model that meets all related regulations and user requirements by using Dynamo visual programming. At last, Navisworks is taken as a 4D simulation tool to present several risk scenarios in order to educate workers and mark the checkpoint for safety managers for improving scaffolding safety management.

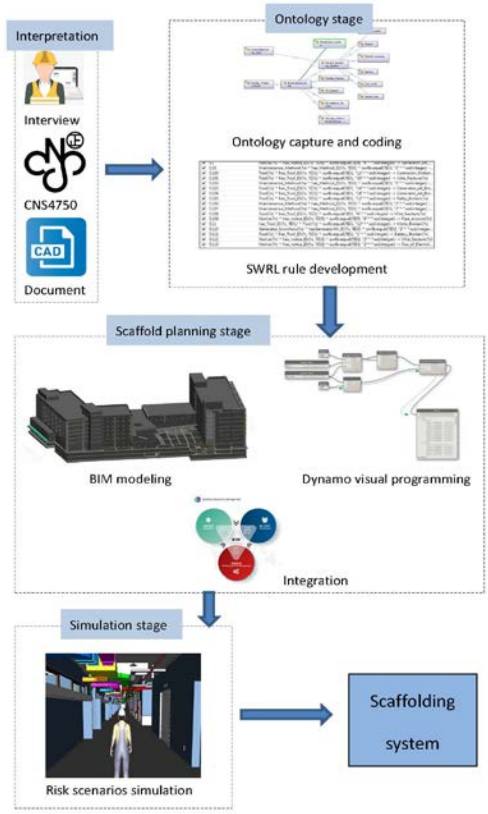

Figure 4. A framework of using BIM to automate scaffolding planning for risk analysis

4.1 Analysis of Scaffolding System Characteristics and Regulations

The scaffolding system, as a temporary structure on a construction job site, is prescribed by the Construction safety regulations or standards, Labor Safety and Health Act, and CNS (Chinese National Standards), the material or manufacturing standards required by the Taiwan government, in which scaffold-related standards are described by CNS4750 and CNS4751. CNS4750 focuses on material and specification of size while CNS4752 focuses on strength performance. On the other hand, work environment and method of assembling scaffolds are set by the Construction safety regulations or standards and Labor Safety and Health Act.

In this study, the scaffold-related standards or laws are extracted and divided into two classes- "quantified standards" and "descriptive standards". Take descriptive standards for instance, in No. 60-1 of Construction Safety Regulations or Standards, whenever the system uses frames, horizontal braces or cross braces, those elements should be assembled with plugs to form a container structure, and its cross section should not be tied by ropes or wires. On the contrary, Construction safety regulations or standards No. 59 states when using wall connectors, the distance between the building walls and the scaffolding system cannot exceed 5.5m in the vertical direction and 7.5m in the horizontal direction in the. The "descriptive standards" describe element's properties in ontology model, and the " quantified standards" are presented by SWRL rules.

4.2 Analyze the Relationship Between Building Condition and Scaffolding Planning

The scaffolding systems are planned according to the various forms and shapes of the building, the site surrounding, and location of entrance. The result of such planning is also influenced by the subcontractor's experiences.

To obtain the method of planning scaffolding, we have interviewed several scaffolding subcontractors and site directors, and divided planning factors into two kinds- one is decided by the user, usually the site director, while the other is not. For example, height, planning area, and location of entrance can be decided by site directors, whereas the shape of building usually dictates where the scaffold should be placed.

4.3 Scaffolding System Risk Analysis

The risk issue of scaffolding system is extracted and integrated from the occupational disasters statistics and the scaffolding suggested checklist by the Institute of

Labor Occupational Safety and Health, the Ministry of Labor. As shown in Figure 5, the issue of scaffolding hazard is mainly consistent with construction site and weather phases which are subdivided into several risk categories.

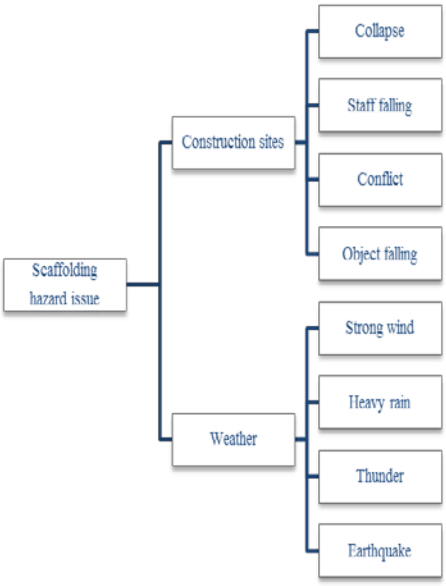

Figure 5. The hierarchy of scaffolding hazard issue

This study uses an approach to identify the cause of each hazard. Sometimes there can be more than one, and the corresponding countermeasures are integrated for each and coordinated with scaffolding and safety elements. Part of the result of integration is shown in Table 1.

4.4 Ontology Modeling

This study analyzed the process of building an ontology model. Figure 6 is a zero stage IDEF0 in which the interview information and literature review are the input data and the output is the scaffolding hazard and planning model which is controlled by scaffolding planning method and ontology modeling specification. The mechanism contains scaffolding subcontractor, site director, ontology developer and BIM developer.

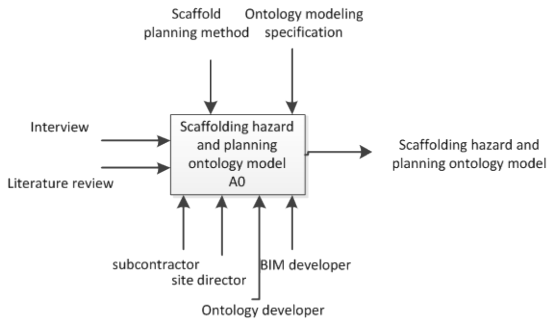

Figure 6. IDEF0 in A0 stage

Table 1. Related elements of hazard

Hazard	Reason	Countermeasure	Related elements
Collapse	Poor structural design	Over 5m scaffolding system should be design by engineer	
	Poor material quality	Standard test by CNS4750	all elements of scaffolding
	Scaffolding unproper fixation	Assembling by standards and using angle brace if needed	all elements of scaffolding
	Poor fixation between building and scaffold	Using wall connector: vertical direction no more than 5.5m, horizontal direction no more than 7.5m	wall connector
	Unstable lower support	Using based plate on lower support	baes plate
	Exceeds the maximum load	Do not stack on scaffolding system	
Staff falling	Double row scaffolding unproper fixation	Do not use wire but swivel coupler to fix	swivel coupler
	Not equipped with safety nets	Scaffold and building spacing greater than 30cm should be set up long strip safety net	safety net
	Staff do not wear helmet and safety harness	Safety manager chek before worker entrance job site	helmet, safety harness

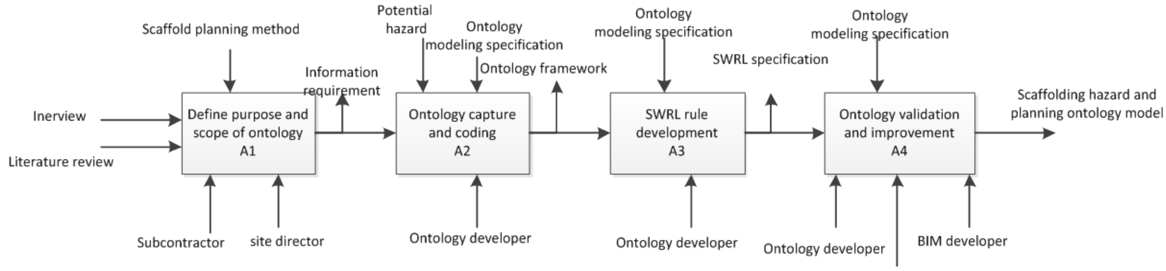

Figure7. IDEF0 in the first stage

There are four steps to build an ontology model in the first stage of IDEF0. Stage A1 defines the purpose and scope of the ontology. A2 establishes ontology capture and coding.A3 initiates SWRL rule development. A4 carries out ontology validation and improvement (see Figure 7)

The main target of building an ontology model is to analyze the information requirement that contains the scaffolding hazard issue and automated planning. The concept of scaffolding hazard and planning ontology model is shown in Figure 8 The relationship between Risk and Elements is denoted by IsRelatedTo, Building shape and Erection Method are linked as hasMethod, and Erection method and Elements are connected by hasElement.

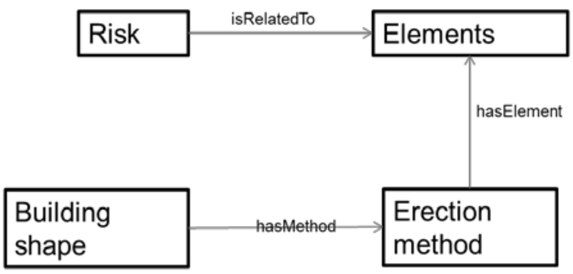

Figure 8. Framework of ontology model

4.5 Automated Scaffolding Planning

This research uses Dynamo to assist Revit to do scaffolding planning, including the BIM elements.

4.5.1 BIM Element

According to the ontology model built in the previous section, the information requirements of scaffolding planning in BIM model have been analyzed, and the requirement-met elements can be designed by using Dynamo visual programming. For instance, the Revit built-in scaffolding element cannot be used in this research because the frame is shared by two scaffolds and we need to design an element that only has one frame per set of scaffold. (See in Figure 9)

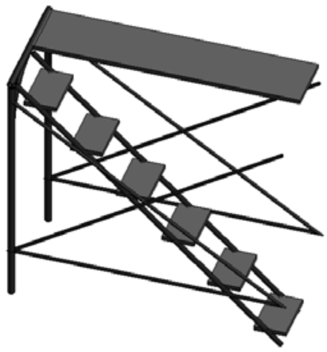

Figure 9. Self-made scaffolding BIM element

4.5.2 Automated Planning of Scaffolding System

In the case of conventional method of planning scaffolding system in BIM models, elements should be placed and angles adjusted one by one which is not only time-consuming, but also error-prone. In order to deal with the problem, following the requirement from the ontology model, " quantity standards" are extracted to program an automated planning code via Dynamo. The operation steps are, (1) click the bottom line of first layer scaffold, (2) select the level where elements should be placed, (3) input how tall the scaffolding system is, (4) set the span and height of one scaffold, (5) calculate how many sets of scaffold are required to be used according to the length and height acquired in steps 1 and 3, (6) position connection points to the exterior of the building, and (7) place the scaffolding elements. The Dynamo module is presented in Figure 10 and the result is shown in Figure 11.

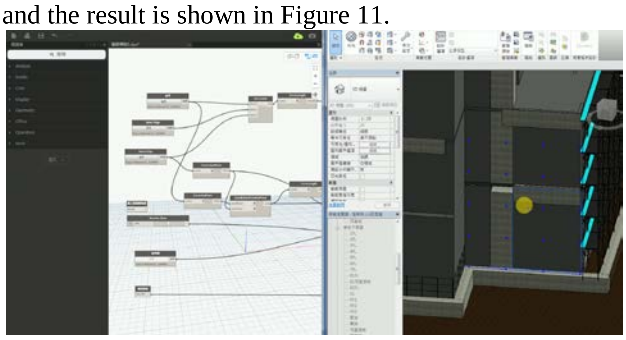

Figure 10. Dynamo module of scaffolding automatic planning

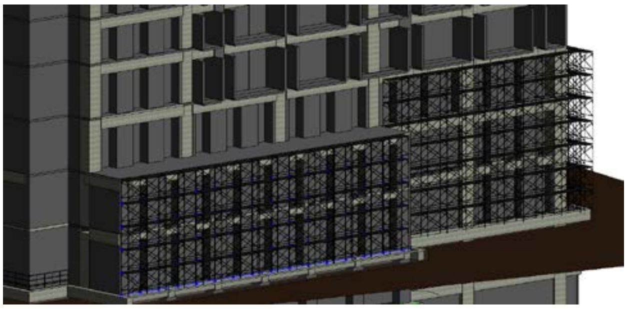

Figure11. Automated planning of scaffolding system

4.6 Safety Simulation

Animation is a powerful tool to provide visualization of the construction process and logistics. By taking advantage of animation, scenarios of unsafe worker behaviors and practices can be simulated for the purpose of educating workers about job site safety issues. For example, Figure 12 shows the result of a simulation depicting the removal of a cross brace by a worker. The simulation is done with Naviesworks.

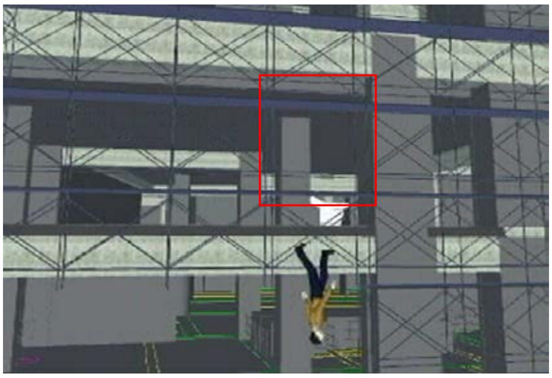

Figure 12. Animation of unsafe behavior simulation

Besides, the Naviesworks model can confirm each checkpoint (Figure 13 and Table 2) has met its safety requirement for safety managers to improve scaffolding safety management and reduce the number of hazards at construction sites.

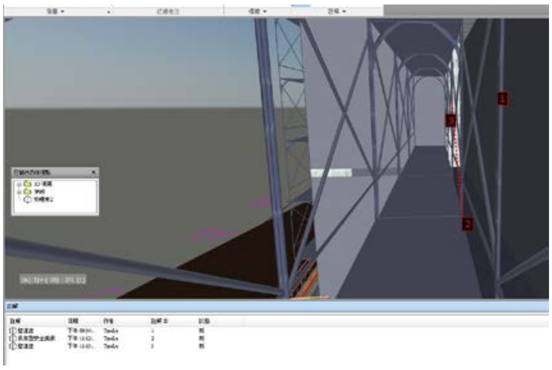

Figure 13. The checkpoints marking model

Table 2. Checkpoints list

<長條型安全網明細表>

A	B	C	D	E	F
族群	族群與類型	建物	建築面	網格位置	連結建物樓層
M_箱	M_箱: 長條型安全	物理棟	南	3S	2
M_箱	M_箱: 長條型安全	物理棟	南	3S	2
M_箱	M_箱: 長條型安全	物理棟	南	3S	2
M_箱	M_箱: 長條型安全	物理棟	南	3S	1
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M_箱	M_箱: 長條型安全	物理棟	南	1S	1
M_箱	M_箱: 長條型安全	物理棟	南	5S	2
M_箱	M_箱: 長條型安全	物理棟	南	4S	1

5 Conclusion

This study presents a framework of using BIM to automate scaffolding planning for risk analysis. Not only did we extract all scaffolding-related standards and laws, but also integrated all kinds of scaffold hazard and planning methods. We have also created an ontology model that includes all the risk elements. Moreover, the ontology model is a shareable, and expandable. New information can be added to the model if needed in the future. We also proposed a method of automatically planning scaffolding by Dynamo visual programming, and it indeed raised the effectiveness of placing elements in the BIM modeling. However, it still has some limitations: the surroundings such as buildings next to the project, which are important planning factors, usually don't show up in the BIM model, hence underestimating the environmental influences in planning scaffolding systems by the BIM model.

6 Acknowledgements

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