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Safety Risk Management of Prefabricated Building Construction Based on Ontology Technology in the BIM Environment

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Abstract: The extensive application of building information modeling (BIM) technology has brought opportunities and challenges to safety risk management in the field of prefabricated building construction. It is of great significance to provide timely information and knowledge for safety risk decisions in prefabricated building construction, and to display this information visually. In response, based on the ontology theory and using the Revit software, in this study we aimed to establish a monitoring system for the construction of prefabricated buildings, which was verified through a practical case. The results revealed that, first, ontology technology can be applied in the Revit software through plug-in integration, and knowledge regarding construction safety risk management in prefabricated building construction can be shared, reused, and accumulated using this system. Second, problems with the design and construction models of prefabricated buildings that do not meet the specification requirements can be detected by the monitoring system in the Revit software. Third, automatic risk identification and response methods using ontology theory and BIM technologies can effectively promote construction safety risk management performance in relation to prefabricated buildings. These findings examine the application of ontology to the field of prefabricated construction safety risk management for the first time, enrich the research on ontology technology, and contribute to safety risk management in the construction of prefabricated buildings.

Keywords: ontology technology; BIM environment; prefabricated buildings; safety risk management; case study

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1. Introduction

Prefabricated buildings are composed of materials that can be prefabricated in a factory, transported to a site for installation, and assembled with the use of post-casting concrete [1]. The use of prefabricated buildings is regarded as an effective approach for improving construction processes and productivity, which can ensure better construction quality and reduce time and cost [2]. Due to advantages such as increasing construction efficiency, improving building quality, and reducing construction waste from the source [3,4], prefabricated buildings have been widely applied in many countries, and this has fostered substantial changes in the development of the construction industry worldwide in recent decades [5].

Although prefabricated buildings are a developing trend in the construction industry in China, the industry still exhibits some gaps in many aspects compared with the industries of many developed countries [6]. Construction safety risk management for prefabricated buildings is an important aspect of this knowledge gap [7]. Specifically, there are some defects in the construction safety risk management of prefabricated buildings. First, there has been a failure to capture the risk precursor information involved in the process of prefabricated building construction in a timely manner [8,9]. Second, it is difficult to integrate and excavate the body of experience and knowledge on prefabricated building construction [10]. Third, because the dynamic nature of prefabricated building construction projects results in changes to safety needs, it is difficult to identify the potential fall hazards at different construction stages according to static drawings [11].

BIM technology, which has been widely used and is the mainstream technology used in the construction industry, has the following advantages. First, it enables participants in prefabricated building projects to communicate and obtain accurate building information. Second, it provides a reliable information-sharing and delivery platform for prefabricated building design, production, transportation, construction, and maintenance [12,13]. Compared with the traditional model, the intervention of BIM technology can improve work efficiency and quality, reduce errors and risks, and significantly reduce costs [14]. These advantages of BIM make it widely discussed, especially in relation to the safety risk management of prefabricated building construction, as it combines such advanced technologies as ontology, the Internet of things (IoT), and artificial intelligence (AI) [15–17]. However, research on this technology is still far from sufficient. First, the applications of ontology technologies in the construction industry have mainly taken place in traditional engineering fields [18] such as water conservancy, municipal administration, railways, subway engineering fields [19,20], etc. Construction in these fields uses traditional technological methods, which are less frequently involved in the field of safety management in prefabricated building projects. Second, although ontology technology has been applied to the construction industry, the automatic creation of ontology instances has seldom been created [21,22]. Finally, there are both cost and efficiency problems when BIM applications are developed separately, or when rules are expressed in code or in a proprietary format [23].

Therefore, the research questions are as follows: (1) What are the safety risk precursors of prefabricated building construction? (2) How can the safety risk knowledge of prefabricated buildings construction be shared and reused? (3) How can intelligent safety risk management of prefabricated buildings by BIM technology be realized?

To bridge the above research gap, this study aims to visually display unsafe factors and pre-control measures in Revit software. The problem of prefabricated building construction safety management has been studied by others; however, ontology technology has never been used in this field. Based on ontology theory, and using the secondary development of the Revit software, a construction safety risk management system for a prefabricated building in a BIM environment was established and then verified empirically through a real case. The findings provide real-time and comprehensive safety risk identification results and solutions for prefabricated building construction professionals, which can effectively lower the difficulty of the work of managers and improve the accuracy of construction safety risk management.

The scope of this study is limited to the safety management of prefabricated building construction. Section 2 presents a literature review and the rationale for this research. Section 3 describes the four steps of the research methodology. Section 4 shows a case study. Section 5 provides the innovations and a discussion. Subsequently, Section 6 summarizes the overall research content and the shortcomings of the study.

2. Literature Review

2.1. Safety Management in Prefabricated Building Construction

Safety management in prefabricated building construction has been studied intensively in the past decades. Safety management is the process of controlling safety policies, practices, and procedures on construction sites [24]. The main aim of construction safety is to prevent accidents [25]. Without effective planning, control, and monitoring, accidents may occur [26]. The identification of risk factors is the premise of safety risk management in prefabricated building construction. It has been deeply studied by many scholars.

Grounded theory (GT) has often been used to identify risk factors regarding the safety of prefabricated building construction, and a conceptual model of the risk factors has been established [27]. For example, Mao and Li [28] analyzed several major risks that may affect the construction process, including risks relating to the transportation and storage of prefabricated components, the waterproofing of prefabricated exterior walls, and the safety of construction sites. Moreover, Jeong et al. [29] built an accident cause map to analyze safety risk factors, and pointed out that defective materials and equipment are important factors causing accidents in the construction stage of prefabricated buildings. In particular, risk management, immediate supervision, and worker's actions are considered by many scholars to be the key causal factors [30].

Correspondingly, establishing a scientific and accurate safety evaluation system for prefabricated building construction can enable accurate judgements of the safety level of prefabricated building construction projects [20]. At present, knowledge from many fields has been applied to the development of construction safety evaluation systems. For instance, attribute mathematics theory has been applied to prefabricated building construction safety evaluation [31]. The expert investigation method is used in the field of prefabricated building construction safety management to screen out relevant factors influencing the construction project [2]. Similarly, structural equation modeling (SEM) has been applied to establish a comprehensive prevention and control system for the component-hoisting process of prefabricated buildings [32].

In addition, the application of IoT intelligent digital technology in the safety management of prefabricated building construction can also improve the efficiency of safety management [16]. For this reason, a model of a prefabricated building project risk management system was established based on the modified teaching–learning-based optimization algorithm and a prediction model of a deep-learning multilayer feedforward neural network [33]. Additionally, Tian et al. [34] adopted the BIM platform for visualization, employed an intelligent monitoring system and manual monitoring as data sources, and utilized the strong prediction capability of a back-propagation neural network to predict safety risks. A digital twin hoisting safety risk coupling model was built, which integrates the methods of IoT, BIM, and safety risk analysis, and this made it possible to complete the fusion of information between the hoisting site and the virtual model to realize visual management [35].

2.2. Ontology Technology in Construction Safety Management

In the field of building safety management, rule-based approaches have attracted increasing research interest [36]. According to Studer et al., an ontology is a formal and explicit specification of a shared conceptualization [37]. In essence, ontology formalizes knowledge by classifying objects, attributes, and logical relationships between objects in a particular domain to facilitate the integration, retrieval, and reuse of information [38]. It plays an important role in the semantic representation and reuse of safety management knowledge [39]. One of the development trends in ontology technology in the field of construction engineering is the integration of ontology technology with BIM technology [20], so that the corresponding automatic risk identification and early warning systems can be designed and developed for risk management [40].

At present, the ontology technology research in construction safety management has focused mainly on the knowledge and semantic reasoning in relation to traditional engineering projects and subway projects. In the field of traditional engineering projects, many scholars have conducted various studies employing ontology technology. For instance, the ontology of specific operational steps for construction activities and the potential hazards in job hazard analysis was established by Wang and Frank [18], and a set of ontology reasoning mechanisms was built to manage the safety risks of related construction activities based on safety rules. A construction safety checking (CSC) ontology was established by Lu et al. [21], which consists of five categories: line of work, task, precursor, hazard, and solution. As described, the method of combining a computer vision algorithm with a formal ontology model can be used to build a safety management system for prefabricated building construction [41].

With the development of ontology technology, experts began to study how to obtain information from heterogeneous data sources to automatically create ontology instances. Semantic Web Rule Language (SWRL) rules were applied to automatically extract information on the masonry components in BIM, forming an automatic safety planning system [11]. Furthermore, a fast regional convolution neural network was used to extract scene elements from a construction site surveillance video, and the elements were transformed into an ontology semantic network [42]. After successfully identifying the video or model of the construction site automatically, the ontology technology can be used to complete the construction safety monitoring. For example, an automated hazards identification system was developed by Xiong et al. [43], which evaluated the operation descriptions generated by means of a live video according to the security standards extracted from textual documents with the assistance of the ontology approach. Likewise, a model using ontology-based semantic trajectories for dynamic environments was applied by Arslan [44], and the output of the Viterbi algorithm was visualized using a BIM model in order to identify the most probable high-risk locations involving sharp worker movements and rotations.

2.3. BIM in the Planning Stage

BIM plays an important role in the construction-planning stage in the field of architecture. On the one hand, BIM technology can optimize the design process to create a safer construction environment [45]. Furthermore, on the premise of safety in the design stage, Teo et al. [46] put forward a conceptual model and certificated that BIM could be an effective tool for improving safety performance. On the other hand, it can be concluded that the decision-making time in the planning stage can be reduced by using BIM technology, thus ensuring that the project is completed on schedule [47].

Typically, the attributes of objects and metadata in BIM are used to control spatial objects. "Simulation and analysis" of a scientific collaboration platform for project participants in the planning stage can be provided by using digital construction models [48,49]. Moreover, the application of BIM in the planning stage can prevent or reduce the generation of construction waste [50].

3. Research Design

Figure 1 presents the main research framework of this study. In the figure, the four blue arrows indicate the different methods used in each step. The overall research framework of this study can be divided into four steps: (1) building the safety risk management system for prefabricated building construction, (2) establishing the prefabricated building construction safety risk ontology library using the improved seven-step ontology modeling method, (3) using the SWRL and the Drools Reasoning Engine to design the automatic risk reasoning function, and (4) developing an intelligent safety risk management system through the secondary development of the Revit software using the C# programming language.

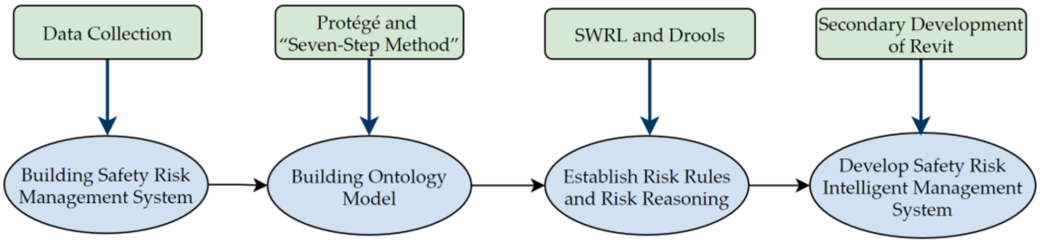


Figure 1. Research framework.

3.1. Building of Safety Risk Management System

Figure 2 reflects the mapping relationship among W, F, A, and M in the construction safety risk management system for prefabricated buildings. The W set represents the work activities of all participants in the construction stage in a certain order. The A set represents the risk of accidents. The F set represents the influencing factors of accident risks. The M set corresponds to the preventive and control measures for accident risks. There are eight numbers in the figure, which represent the steps involved in the research process. The black arrows represent the path relationships among the four processes, and the blue arrows stand for the methods that need to be used among the four processes.

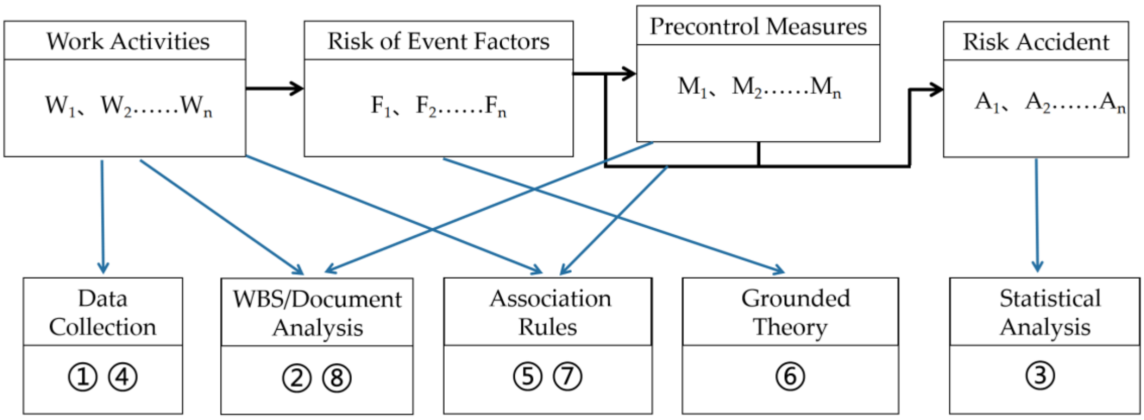


Figure 2. Research paths involved in safety risk management.

The flow content for each number in Figure 2 is described below:

(1) A large number of case reports for prefabricated building construction accidents are collected from relevant domestic government websites, construction logs, and interview records.
(2) The work breakdown structure (WBS) and a literature analysis are used to clarify the specific composition of the work activity set.
(3) By consulting accident investigation reports and construction logs, the composition of the accident risk set is analyzed according to relevant national industrial injury classification standards.
(4) The accident investigation reports, construction logs, and interview records are randomly divided using a ratio of 7:3.
(5) The accident investigation reports and construction logs are analyzed using association rules to clarify the mapping relationship between set W and set A.
(6) Based on grounded theory, 70% of the accident investigation reports, construction logs, and interview records are analyzed to examine the specific composition of set F (risk precursor event factors). The remaining 30% are used to test the saturation of the specific components in set F.
(7) The mapping relationships between set F and set W, and between set F and set A, are clarified by discussing 70% of the accident investigation reports and construction logs with association rules, and the remaining 30% are used to test the correctness of the specific components in set F.
(8) Through an analysis of the literature, targeted prevention and control measures aiming at different risk factors are extracted.

We were able to construct a safety risk management system for prefabricated building construction through the above methods, thus laying a foundation for the construction of the subsequent ontology.

3.2. Establishment of Safety Risk Ontology

With the increasing safety knowledge regarding prefabricated building construction, the traditional seven-step method relies too much on labor, which can no longer meet the requirements of ontology construction. Therefore, an improved seven-step method was adopted to develop the safety risk ontology for prefabricated building construction. Figure 3 presents the four critical steps involved in building an ontology model using the improved seven-step method. As shown in this figure, the safety risk ontology model for prefabricated building construction was semi-automatically built on the Protégé platform based on ontology theory and using the improved seven-step method. First, combined with the risk-control logic for prefabricated building construction, the top-level category of ontology was divided into engineering projects, construction activities, precursor information, risk status, and preventive measures. Second, the expression characteristics of terms and clauses in standards and specifications were analyzed, and the screening rules for these characteristics were formulated. Third, according to the rules, the 226 selected terms were extracted, clustered, and extended by the category's central words, so that all subclasses and hierarchical relationships of top-level ontology classes were defined. Fourth, by defining the object-oriented attributes, data-oriented attributes, and the attribute constraints of the classes, a complete ontology knowledge base of safety risks in prefabricated building construction was formed.

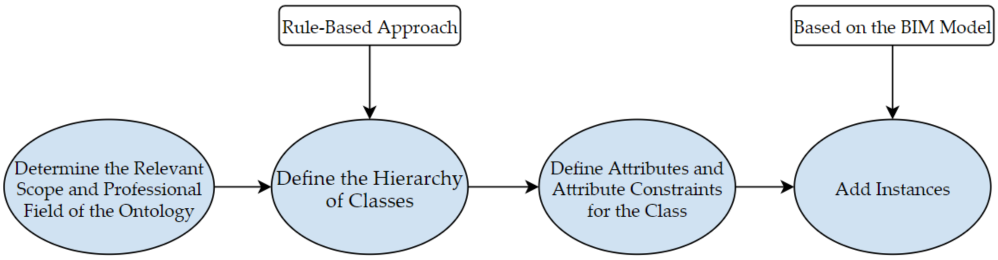


Figure 3. The ontology-modeling process of the construction safety risk knowledge base.

Figure 4 shows a hierarchical diagram of the final ontology. In Figure 4, the five terms in blue boxes express the top five categories of the ontology. The sixteen terms in green boxes represent the subclasses of the top-level ontology classes. The six terms in white boxes indicate the specific contents of the factors that affect the safety risks in prefabricated building construction, such as lifting injuries, vehicle transport injuries, mechanical injuries, and so on.

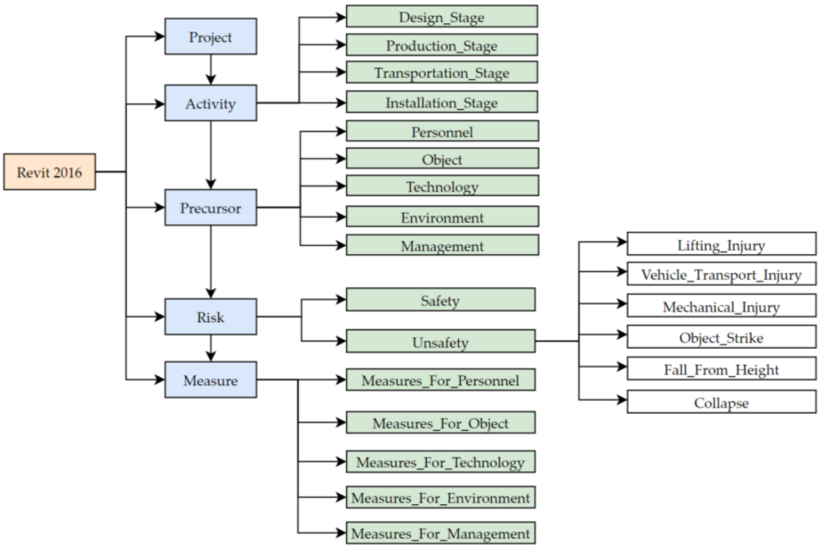


Figure 4. Ontology view of safety risk management.

3.3. Reasoning for Construction Safety Risk Ontology Based on Rules

The safety risk rules for the construction of prefabricated buildings were first defined, consisting of two parts. One part of these rules was extracted from the norms relating to the safety risks of prefabricated building construction, and the other part was obtained by using the concept lattice method to dig deeply into the accident cases involving prefabricated building construction. The construction safety risk rule library for prefabricated buildings was then obtained, including risk subjects, risk discrimination conditions, risk events, and preventive measures, in four parts.

Furthermore, the automatic application of the risk rule base was realized. The safety risk rules were structurally expressed in the SWRL language with the semantic reasoning function, which can be recognized by means of a computer, and stored in the Protégé 5.5 platform through the SWRL Tab plug-in. Figure 5 shows the Protégé interface for the input operation of the SWRL rule; its main interface path is: Windows/Views/Ontology views/Rules.

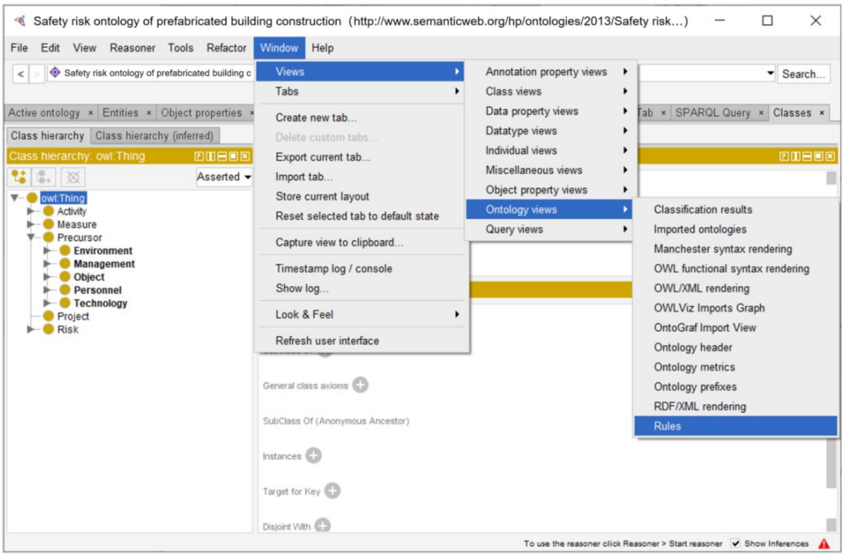


Figure 5. SWRL rule entry in the Protégé interface.

On the basis of ontology knowledge and the safety risk rule, the inference results were shown in the Protégé platform by means of the Drools reasoning engine, which provides support for the intelligent management of the construction safety risks for prefabricated buildings. A flowchart of the ontology reasoning process based on Drools is shown in Figure 6. There are two important tasks depicted in Figure 6. First, the ontology OWL knowledge and SWAL rules were transformed into Drools rule language. Second, the Rete algorithm was used to match the Drools rules to achieve reasoning, and the reasoning results were automatically updated in the ontology knowledge base.

3.4. Integration of BIM and Ontology

Intelligent safety risk management in prefabricated building construction should integrate BIM technology and ontology technology. Furthermore, the application points of BIM technology in different stages of prefabricated building projects should be analyzed. On this basis, the Revit software was selected as the bearing platform for the intelligent safety risk identification system integrating BIM technology and ontology technology, and the safety risks of prefabricated building construction were intelligently identified in the design and construction stages.

Figure 7 provides a logical model of the intelligent safety risk management process for prefabricated building construction. The logical model contains the integration of BIM technology, prefabricated building ontology, and the ontology safety risk rule base. As mentioned in the figure, in order to realize the development of system functions, an intelligent risk management logical model integrating BIM technology and ontology technology was established, and the mapping mechanism between BIM technology and ontology technology was clarified. Moreover, through the programming detection algorithm implemented in the Java language, the mapping from an Industry Foundation Classes (IFC) file containing rich data information from the BIM model to a Web Ontology Language (OWL) file of ontology was realized. Then, the transformation from component information in the BIM model to ontology instances and instance attributes was completed.

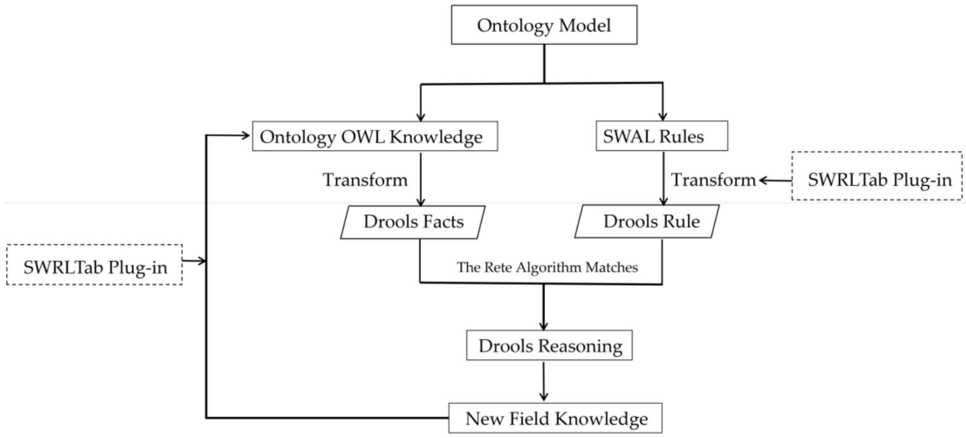


Figure 6. Ontology reasoning process based on Drools.

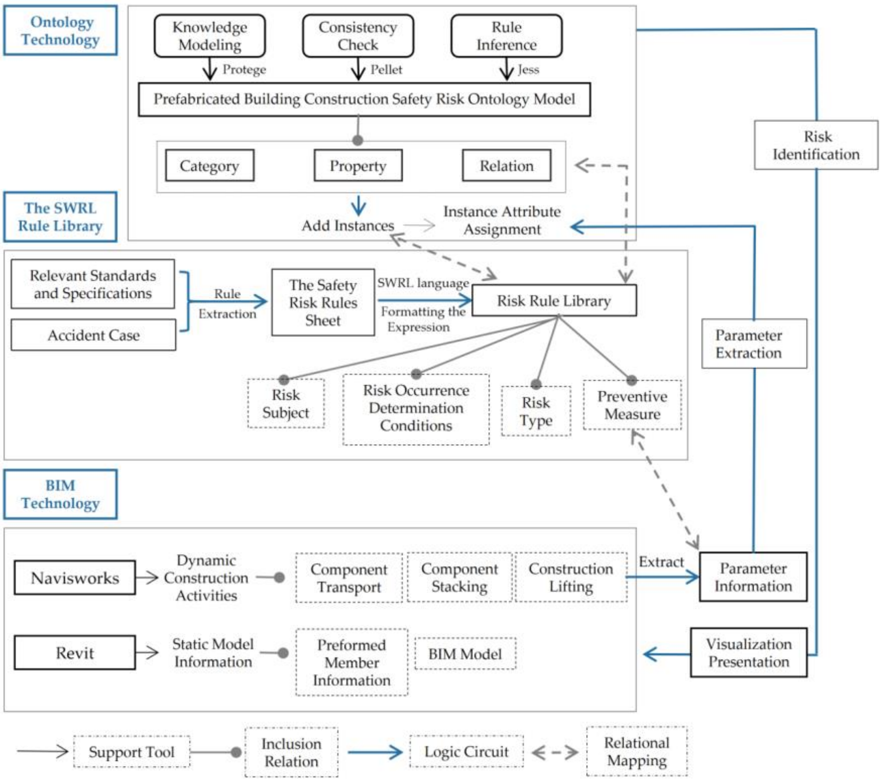


Figure 7. Logical model of the intelligent management of safety risk.

A flow diagram of the risk identification mechanism is presented in Figure 8. Specifically, when the identification program is started and the risk identification object is a specific component in the BIM model, the program matches the name of the component with the risk subject obtained from the rule base. The related component parameter information can be mapped onto the risk ontology via a detection algorithm, which automatically creates instances and matching attributes. Then, the risk state can be identified by means of SWRL rules and an inference engine in the Protégé software. The corresponding measures are implemented when the risk state is determined to be "unsafe". On the contrary, when the risk state is safe, the identification program will continue to detect the next component name, as shown in the flow chart. The intelligent identification mechanism of safety risk integrated with BIM technology and ontology technology is analyzed below. According to the different attributes of risk subjects, two different types of risk subjects are discussed in the BIM environment: the static prefabricated components in the design stage and the dynamic work activities in the construction stage. Then, the mechanism of intelligent risk identification is completed by combining ontology reasoning methods.

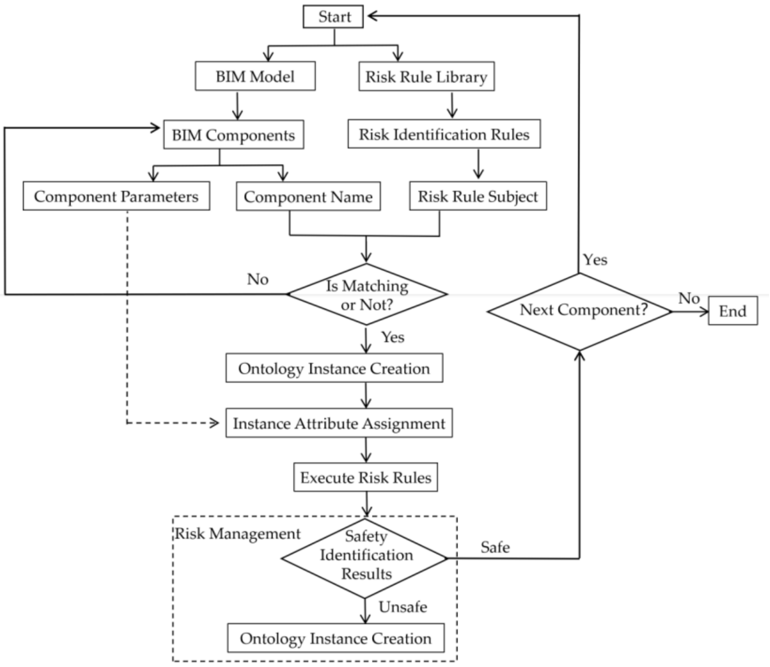


Figure 8. Risk identification mechanism.

In addition, the intelligent risk management system was established through secondary development in the Revit software using the C# programming language. Through this system, the visual, automatic, and intelligent management in the design and construction stages of prefabricated buildings can be realized, and the safety risk management ability in relation to prefabricated buildings can be improved. The secondary development process implemented in the Revit software is clarified in Figure 9. With the continuous application of Revit secondary development technology, a relatively unified process step has been created, which includes analyzing requirements and new projects, adding interface files, adding namespaces, adding attributes to command classes and new classes, writing codes, compiling, loading, debugging, and other steps.

As a supplement, we provide the pseudo-code for the development of add-ins in C#, of which the specific pseudo-code is as follows:

```
// first, we need to get the message from Drools and the prefabricated objects from Revit
messages = Risk inference result and measures
objects = Prefabricated objects for Revit
// next, we need to associate corresponding messages and objects
result = Map the messages and objects
// finally, we use a form to show the result
form = new Forml(result)
form.ShowDialog().
```

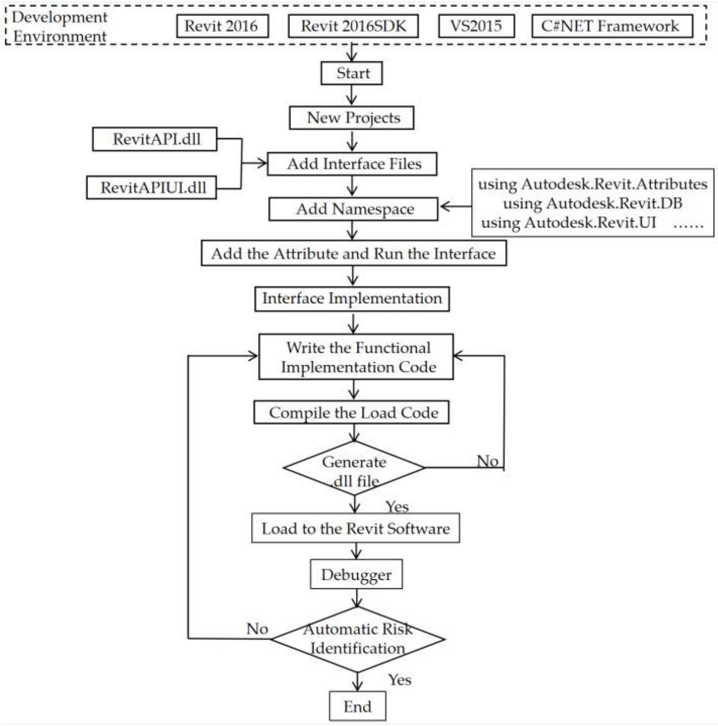


Figure 9. Revit secondary development process.

4. Case Study

4.1. Case Description

In this section, we describe the case study we conducted to verify and demonstrate the proposed reasoning and management system. A newly built residential community in Jiangsu, China was selected as the studied case. This project involved a fabricated shear wall structure, including a fabricated shear wall, fabricated stairs, steel truss composite floor, etc. The prefabricated components and other structures, such as the frame columns and the frame beam, were poured together using concrete. The prefabrication ratio of this project was 31.53%.

According to the design drawings and the construction site layout plan, two models—a design model and a construction model—were established. The design model was used to identify the safety risks of the static prefabricated components in the design stage. Similarly, the construction model was used to identify the safety risks of the dynamic construction process in the construction stage.

4.1.1. Design Model

In this study, a standard layer in the case project was selected to build the design model, and the reinforcement conditions in the prefabricated shear wall were modeled in detail according to the design drawings. Figure 10 shows a standard layer of the project's design model established in the Revit software.

4.1.2. Construction Model

According to the layout drawings of the construction site, risk subjects were set in the construction model, including tower cranes, prefabricated component yards, construction machines, etc. Figure 11 provides the construction model diagram in Revit. The layout of the operation buildings and the tower cranes are included in Figure 11.

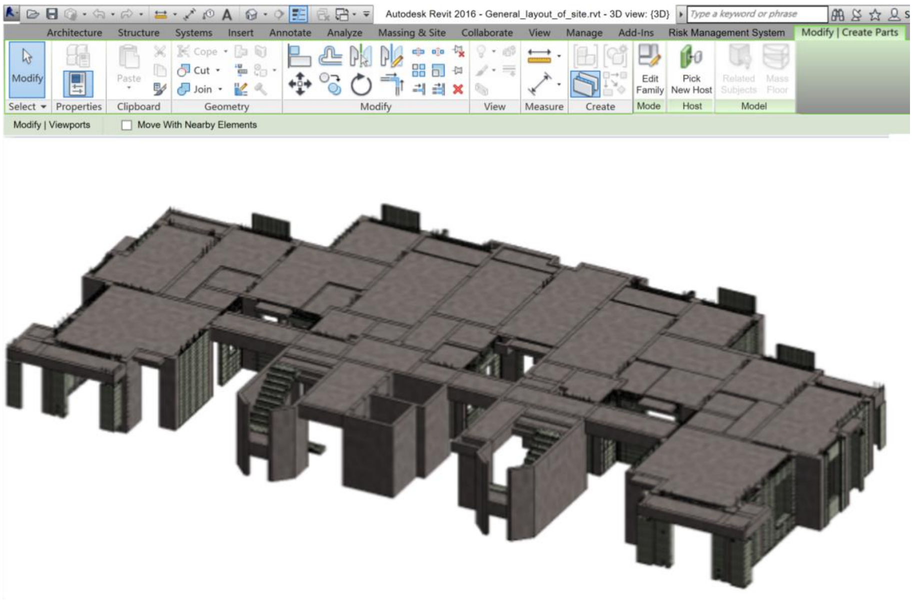
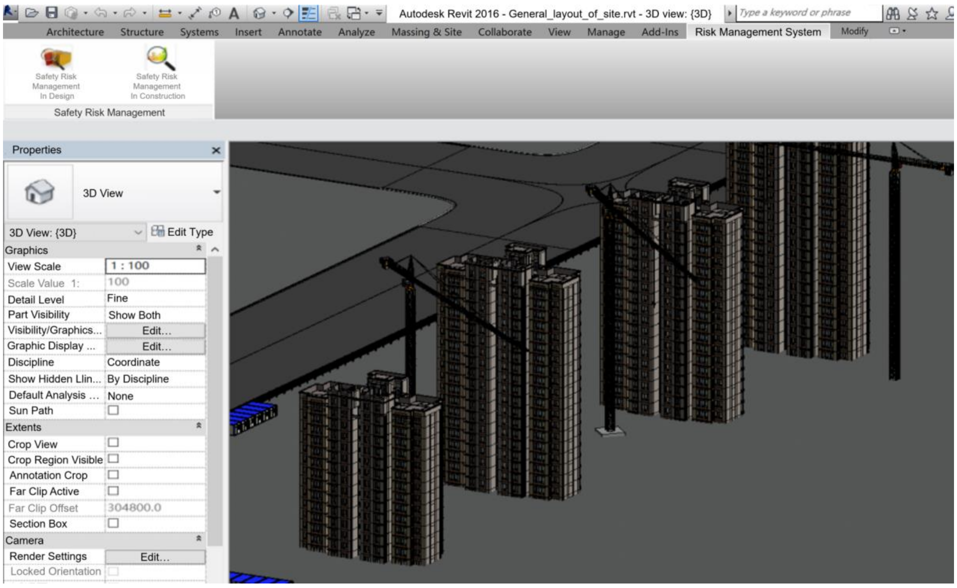


Figure 10. BIM model in the design stage.



Graphics	
View Scale	1 : 100
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Crop Region Visible	☐
Annotation Crop	☐
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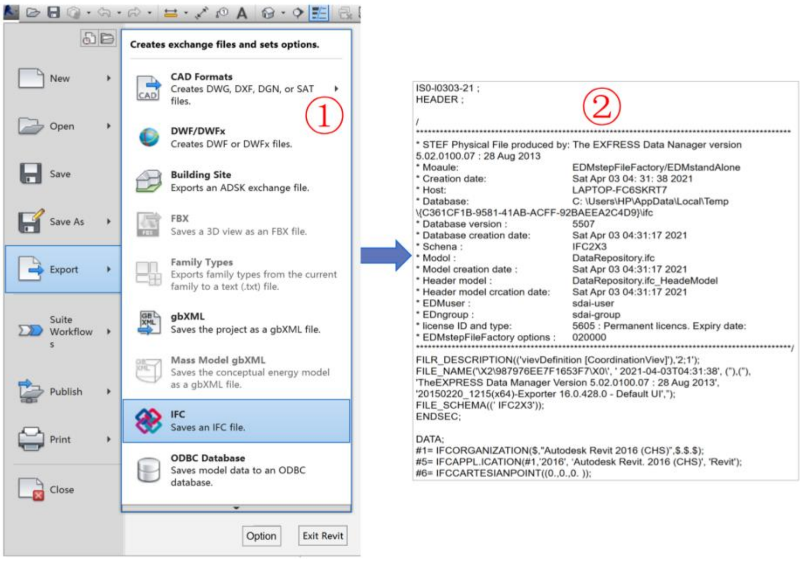
Locked Orientation	☐

Figure 11. BIM model in the construction stage.

4.2. Construction Safety Risk Reasoning Based on Ontology Technology

In this study, the prefabricated shear walls, as components of the case study project, are taken as an example to illustrate the automation and risk reasoning process of ontology instances. The process of exporting IFC files from project files created with the Revit software is shown in Figure 12.

After this exporting step, the IFC documents exported from the design model were scanned by the developed detection algorithm. The express language from the IFC document was detected through Java language analysis and automatically mapped to the OWL language. Then, relevant parameters were extracted and transformed into a recognizable ontology format to form ontology instances and corresponding attribute values. The results obtained in the ontology software are shown in Figure 13. In the figure, the data attribute values for different component examples are indicated with a red box. "YZJLQ-03", for example, represents the precast shear wall, and its data attribute is represented by "has _ the _ size _ of _ hole" 2200 * 1600" ^^ xsd: string", and so on.



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5.02.0100.07 : 28 Aug 2013
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* Database creation date:           Sat Apr 03 04:31:17 2021
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* Modol :                           DataRepository.ifc
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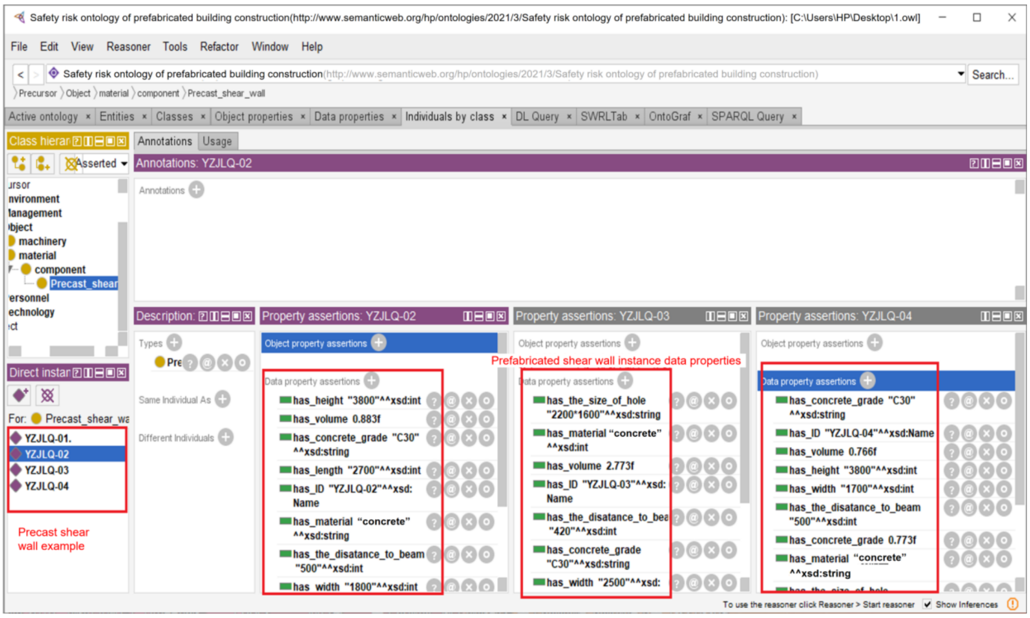
Figure 12. IFC file export process.



Property assertions: YZJLQ-02

Object property assertions

Data property assertions

- has_height "3800"^^xsd:int
- has_volume 0.883f
- has_concrete_grade "C30" ^^xsd:string
- has_length "2700"^^xsd:int
- has_ID "YZJLQ-02"^^xsd: Name
- has_material "concrete" ^^xsd:string
- has_the_disatance_to_beam "500"^^xsd:int
- has_width "1800"^^xsd:int

Property assertions: YZJLQ-03

Object property assertions

Data property assertions

- has_the_size_of_hole "2200*1600"^^xsd:string
- has_material "concrete" ^^xsd:int
- has_volume 2.773f
- has_ID "YZJLQ-03"^^xsd: Name
- has_the_disatance_to_bea "420"^^xsd:int
- has_concrete_grade "C30"^^xsd:string
- has_width "2500"^^xsd:

Property assertions: YZJLQ-04

Object property assertions

Data property assertions

- has_concrete_grade "C30" ^^xsd:string
- has_ID "YZJLQ-04"^^xsd:Name
- has_volume 0.766f
- has_height "3800"^^xsd:int
- has_width "1700"^^xsd:int
- has_the_disatance_to_beam "500"^^xsd:int
- has_concrete_grade 0.773f
- has_material "concrete" ^^xsd:string

Figure 13. Ontology instance creation.

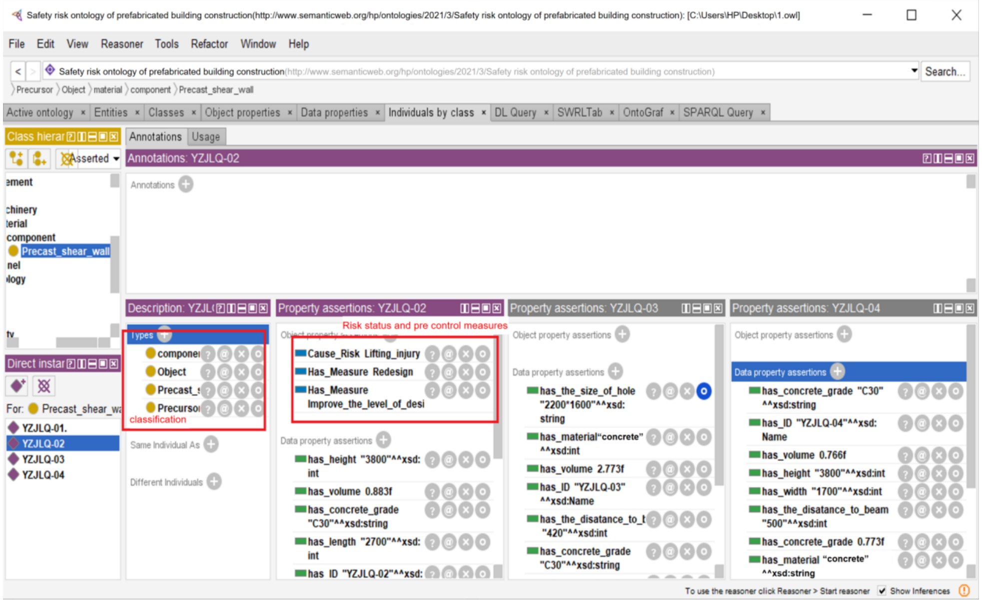
Moreover, "SWRL + Drools" reasoning was performed after adding the instance to the ontology automatically. The result displayed in the software is presented in Figure 14. The following three new descriptions of knowledge reasoning were added for this example:

(1) The object attributes of "cause_risk lifting_injury" were added into the object attribute column for the example with the component ID "YZJLQ-02". This indicates that there were some settings in the design parameters of the shear wall that did not comply with the SWRL rules. "YZJLQ-02" shear wall members were subject to safety risks that may have led to crane injury accidents. This shows that the risk ontology constructed based on the SWRL rule base and the Drools inference engine were capable of inferring the risk status of the components.

(2) The object attributes "has_measure improve_the_level_of_designs" and "has_measure redesign_according_to_standards <JG1-2014> 8.2.1" were added into the object attribute column for the example of the "YZJLQ-02" shear wall. This indicates that measures should be taken to improve the professional level of designers for shear wall

components with safety risks, and risk prevention measures should be redesigned according to Article 8.2.1 of the *Technical Standard for Prefabricated Concrete Structures of the Standard Specification*. Provided with these accurate risk prevention and control measures, designers can quickly correct design errors, which will improve the efficiency of risk management.

(3) The expression of the generic relationship was more comprehensive after the reasoning process. Through the reasoning process, the program changed the category of the prefabricated shear wall from belonging only to the "precast shear wall" class to belonging to the "component", "object", and "precursor" parents in the type column.



Safety risk ontology of prefabricated building construction(http://www.semanticweb.org/hp/ontologies/2021/3/Safety risk ontology of prefabricated building construction): [C:\Users\HP\Desktop\1.owl]

Property assertions: YZJLQ-02

Risk status and pre control measures

Cause_Risk Lifting_injury
Has_Measure Redesign
Has_Measure Improve_the_level_of_desi

Data property assertions

has_height "3800"^^xsd:int
has_volume 0.883f
has_concrete_grade "C30"^^xsd:string
has_length "2700"^^xsd:int
has ID "YZJLQ-02"^^xsd:

Property assertions: YZJLQ-03

Data property assertions

has_the_size_of_hole "2200*1600"^^xsd:string
has_material"concrete" ^^xsd:int
has_volume 2.773f
has_ID "YZJLQ-03" ^^xsd:Name
has_the_disatance_to_t "420"^^xsd:int
has_concrete_grade "C30"^^xsd:string

Property assertions: YZJLQ-04

Data property assertions

has_concrete_grade "C30" ^^xsd:string
has_ID "YZJLQ-04"^^xsd:Name
has_volume 0.766f
has_height "3800"^^xsd:int
has_width "1700"^^xsd:int
has_the_disatance_to_beam "500"^^xsd:int
has_concrete_grade 0.773f
has_material "concrete" ^^xsd:string

Figure 14. Ontology reasoning results.

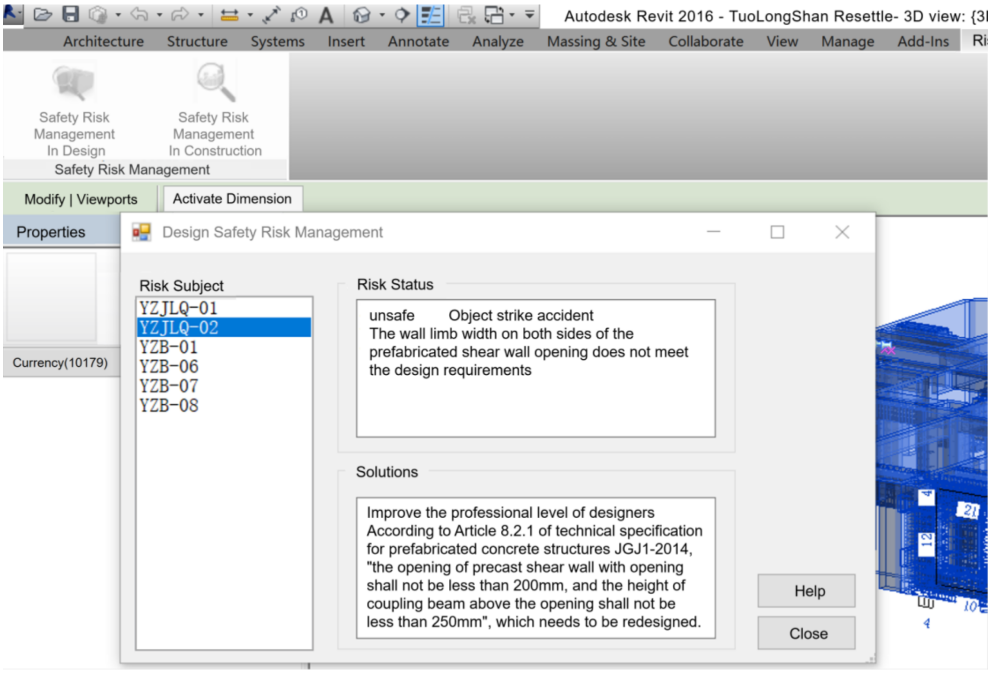
4.3. Integrating BIM Technology with Ontology Technology

The risk status and solution measures of the risk subject inferred by ontology were stored and displayed in the ontology editing tool interface. The results of the partial ontological risk inference were imported into an Excel document by hand in the order of "risk subject name/ID–risk status/parameter items not satisfying rules–solutions/prevention and control measures". Then, the Excel document was associated with the code related to the Revit secondary development using the C# language.

4.3.1. Safety Risk Management in the Design Stage

The ontology knowledge was realized with the help of the plug-in function "safety risk management in the design stage". The design safety risk status of each component in the design model was reviewed by automatically checking the design parameters of individual fabricated members. In addition, the corresponding solutions were automatically generated. These results were visually displayed in the BIM model by means of the Revit plug-in, enabling designers to modify the design parameters of components and avoid the omission and misjudgment of the design provisions in the traditional review process. Eventually, a BIM model with parameters that met the specification requirements was obtained.

A BIM model with an accurate design stage can be applied directly to the industrialization of prefabricated components and the mechanization of production methods, so as to realize the automatic production of components. In the Revit interface, we selected all the components in the design model, and then clicked the "design safety risk management" plug-in button. The results of the intelligent risk identification system are shown in Figure 15. After the command was executed, the unsafe risk status and solution measures of shear wall members with the component named "YZJLQ-02" were automatically identified. The results of the ontology were presented in the BIM model in a visual form to facilitate the collaborative management of multiple participants involved in prefabricated building construction.



Risk Subject
YZJLQ-01
YZJLQ-02
YZB-01
YZB-06
YZB-07
YZB-08

Risk Status
unsafe Object strike accident
The wall limb width on both sides of the prefabricated shear wall opening does not meet the design requirements

Solutions
Improve the professional level of designers
According to Article 8.2.1 of technical specification for prefabricated concrete structures JGJ1-2014, "the opening of precast shear wall with opening shall not be less than 200mm, and the height of coupling beam above the opening shall not be less than 250mm", which needs to be redesigned.

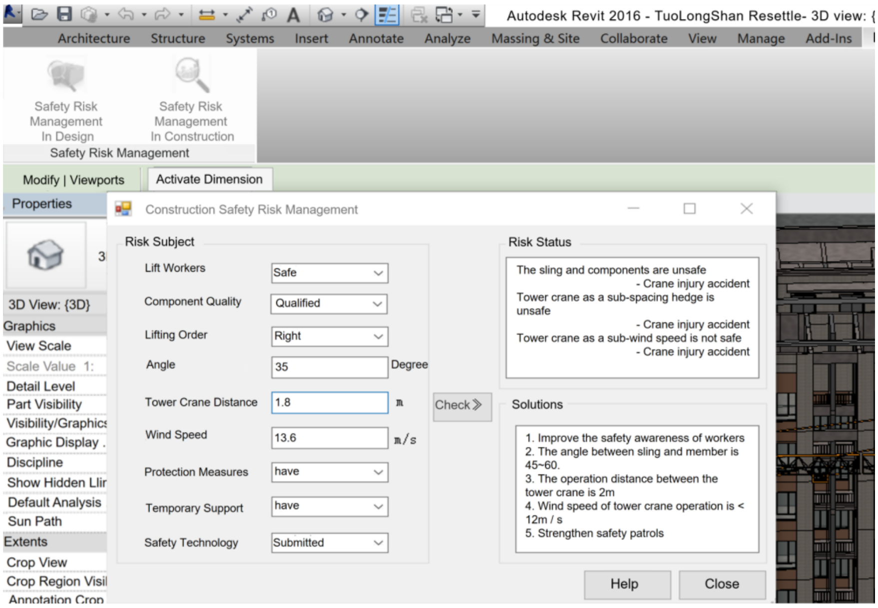
Figure 15. Operation results of the "design safety risk management" function.

4.3.2. Safety Risk Management in the Construction Stage

With the help of the "construction stage safety risk management" plug-in function, the risk factors in the construction process were checked in a timely fashion by the managers. By inputting the status values of risk factors into the plug-in function's interface, the safety status of the current construction process can be intelligently identified, and solutions corresponding to the unsafe status can be automatically generated.

To illustrate this mechanism, an example of two tower cranes was created, and then a value of 1.8 m for the data type property "has_working_distance_between_tower_cranes" was added to express the interval of 1.8 m between the two tower cranes in the BIM model. After the ontology reasoning process, the program displayed "cause_risklifting_error", "has_measure_improve_workers_safety_awareness", "has_measureworking_distance_between_tower_cranes > 2 m", and "has_measuresafety_supervision". The real-time datapoint of 1.8 m in the risk subject "operation distance between tower cranes" was inserted into the plug-in operation interface, and the risk factor status value was inserted. The "check" button was then clicked. The operation results of the risk intelligence system are shown in Figure 16.

After running the software, the display of the risk status and preventive measures was consistent with the ontology reasoning results. This process realized the use of knowledge to identify safety risk factors in the construction phase intelligently, and provided solutions for the factors, which were displayed in the BIM software. Some risk items were defined briefly. For example, the hoisting workers were identified as "safe" or "unsafe", and the component quality was identified as "qualified" or "unqualified". For future research, RFID technology and wireless sensor technology can be combined with these definitions to realize the real-time acquisition and automatic input of risk subject data in the construction process.



Construction Safety Risk Management

Risk Subject

Lift Workers: Safe
Component Quality: Qualified
Lifting Order: Right
Angle: 35 Degree
Tower Crane Distance: 1.8 m
Wind Speed: 13.6 m/s
Protection Measures: have
Temporary Support: have
Safety Technology: Submitted

Risk Status

The sling and components are unsafe
- Crane injury accident
Tower crane as a sub-spacing hedge is unsafe
- Crane injury accident
Tower crane as a sub-wind speed is not safe
- Crane injury accident

Solutions

1. Improve the safety awareness of workers
2. The angle between sling and member is 45~60.
3. The operation distance between the tower crane is 2m
4. Wind speed of tower crane operation is < 12m / s
5. Strengthen safety patrols

Figure 16. Operation results of the "construction safety risk management" function.

5. Discussions

To date, there have been numerous studies presenting BIM-supported ontology development for construction safety risk management, but most studies have been applied to building cost estimation [51,52], green building evaluation [53], construction defect information [54], and technical methods, such as expressing BIM in the semantic web format [55]. This suggests that there are few studies related to the integration of ontology with BIM in the field of the safety management of prefabricated building construction. In this study, a common construction model is used to illustrate the function of integrating ontology technology with BIM technology. The above research shows that the system can detect and avoid design problems caused by non-compliance with the construction specifications at the design stage, which has practical application value.

Many scholars have conducted research in the field of safety risk management, but there are still few research results in the field of prefabricated building safety risk management [56] because there are obvious differences between the prefabricated construction method and the traditional cast-in-place construction approach [57]. The biggest difference between the construction of prefabricated buildings and traditional construction methods is that in the former, a large number of additional hoisting operations are required. Cranes are used for module hoisting because of their excellent transportation capacity in construction [58]. Many scholars have paid attention to the optimal arrangement of tower cranes [59,60]. In our case study, the layout of tower cranes was taken as an example in order to identify the safety risk in the construction model. After identification, the unsafe risk factors and pre-control measures were presented in the Revit program. We thus provided a new method for safety risk management in the preparation stage of prefabricated buildings.

There is no doubt that some advanced technologies can be used to detect risk factors in the construction process, which can reduce the probability of accidents. For example, an intelligent early warning system was established to indicate the safety risk of a metro tunnel, displaying this information in 3D form by means of BIM technology [34]. Ontology and case-based reasoning technologies have been introduced into the field of building safety accident control [61]. Moreover, IoT technologies have been used to monitor the project implementation process in prefabricated building construction [62], which help to optimize construction schedules and ensure the quality and safety of prefabricated building construction projects. In this study, unlike previous research, once the risk factors were identified and detected in the Revit software, the preventive measures were immediately displayed, as shown in Figure 16. This allows managers to quickly adjust the design scheme or construction method by monitoring risk factors in the design and construction stages, thereby reducing the occurrence of prefabricated building construction accidents. Furthermore, it improves the level of intelligent construction safety accident control, thus providing a means of improving accident control technology through the use of scientific and intelligent technology.

In this study, we drew lessons from the existing research to construct a safety risk ontology for prefabricated building construction. Through the prototype of construction risk identification, established in the BIM environment, the automatic identification method of security risks based on a semantic data model was tested [63]. Through an ontology-based framework, with the aim of supporting environmental monitoring and compliance-checking in the BIM environment among different information systems, a specific ontology was developed to represent the relevant knowledge [64]. Furthermore, a meta-model for a construction-safety-checking ontology has also been developed [21] to integrate new technology into construction-safety-checking systems. In this study, a construction-safety-checking ontology, including five primary classes ("line of work", "task", "precursor", "hazard", and "solution"), was proposed to express safety-checking concepts. As described above, from the set point of view, a prefabricated construction safety risk management system including work activities, risk event factors, accident risks, and prevention and control measures was constructed. In addition, the components of each set and the mapping relationships between them were defined. This lays a foundation for the realization of the knowledge-based "risk-prevention-type" management model, and avoids faults due to a lack of mechanisms to formally assess security risks and select safety plan elements [65].

Some researchers have developed ontology methods on the basis of regulatory ontology and additional domain ontology [66], such as building environmental monitoring ontology [64] and practical product ontology [67]. Such developments are relevant to this study. For example, the integration of a modular approach with construction safety risk management based on BIM was introduced by Darko et al., who conducted a critical survey of BIM-based modular integrated construction risk management [68]. Furthermore, a construction safety ontology was proposed by Zhang et al. to formalize safety management knowledge, and a prototype application of ontology-based job hazard analysis and visualization was implemented to further illustrate the applicability and effectiveness of their developed ontology [22]. In this study, the ontology approach was integrated with BIM technology. The results show that the risk factors can be intelligently identified using the Revit software after secondary development. In particular, as expressed in Figure 1, safety risk rules were mined from accident cases with the help of a concept lattice and transformed quickly through the SWRL semantic reasoning language and the Drools reasoning engine. In addition, the intelligent risk reasoning process and the automatic production of reasoning results were realized in the Protégé software. The Drools reasoning engine has good compatibility with the Protégé software. Compared with the Jena reasoning engine and the Jess reasoning engine, the use of Drools avoids the operation of loading reasoning engine plug-ins and configuring the corresponding reasoning environment as part of the reasoning process. Ultimately, through the secondary development of the Revit software with the C# language, an intelligent risk management system was established.

The Revit software was chosen as the development platform based on previous research experience. The advantages and applications of the Revit software include its comprehensive BIM information, clear content, and the ease of the collection and management of information parameters [69]. Previously, a plug-in was developed by Lu et al. in Autodesk Revit to connect BIM and safety risk data, which can automatically calculate construction safety risks and help architects and structural designers to quickly choose design schemes [70]. Furthermore, Zou et al. explored the feasibility and potential of developing a BIM and knowledge-based risk management system. The Revit model was also used to further develop Navisworks to realize 4D functions, such as construction planning, simulation, and real-time navigation [71]. Combined with the above experience, an intelligent risk management system based on Revit secondary development was designed in this study. The software has a wide range of components and parameters, so we were able to use it to create the corresponding prefabricated component family according to the design information for the components of prefabricated buildings, which was suitable for the BIM model construction. Therefore, the intelligent semantic identification of risks involved in the process of prefabricated building construction was realized in the BIM environment. This not only expands the application of BIM, but also provides key resources for the evolution and upgrading of BIM technology from informatization to intelligence.

Ultimately, although the proposed management system can be successfully used for the identification of risk factors in prefabricated building models, the system still needs to be optimized and further developed. Ontology-based construction safety control measures have become effective measures for building safety management in recent years, and also represent the key development direction for safety management for the future in the construction industry [72]. The application of ontology technology in artificial intelligence systems in the prevention of building safety accidents can have various manifestations and can involve various types of safety knowledge in the building field, but it needs to be standardized. Therefore, the following points should be noted in future applications: (1) the risk management system should be regularly updated and improved, such as adding more accident cases, literature analyses, etc.; (2) with the updating of modeling software, the rule base used in ontology construction requires regular maintenance; and (3) more artificial intelligence technologies could be added for the identification of safety risk factors for prefabricated building construction.

6. Conclusions

In practice, with the widening application of prefabricated buildings, safety risk management is becoming increasingly complicated. To provide timely information and knowledge for construction safety risk decisions regarding prefabricated buildings and to display this information visually, a safety risk management system for prefabricated building construction in the BIM environment was established based on ontology theory and secondary development of the Revit software, and it was empirically verified using a real case study. The results showed that, first, ontology technology can be applied in the Revit software through plug-in integration, and the available knowledge on safety risk management in prefabricated building construction can be shared, reused, and accumulated. Second, problems in the design and construction of prefabricated buildings that do not meet the specification requirements could be detected by the monitoring system in the Revit software. Third, automatic risk identification and responses implemented by ontology and BIM technologies can effectively increase construction safety risk management performance in relation to prefabricated buildings. The specific contributions of this study are as follows:

(1) The first contribution is methods innovation. The application of BIM in prefabricated building construction safety risk management can be combined with the knowledge from other fields, such as DT, IoT, etc. However, our study uses ontology technology, which is the first time that this technology has been applied to the safety risk management of prefabricated building construction. This study provides a complete technical scheme for the efficient reuse of historical project information and knowledge to assist managers in risk decision-making.

(2) The second contribution is functional innovation. Once the risk factors were identified and detected using the Revit software, the preventive measures were directly displayed. This allows managers to quickly adjust the design scheme or construction method by monitoring the risk factors in the design or construction stages, thereby reducing the occurrence of prefabricated building construction accidents.

The safety risk management system for prefabricated building construction in the BIM environment established in this study also has some limitations. First, although a substantial body of risk rules have been included, there are still risk rules that have been ignored in the current study. Moreover, the extraction of complex reinforcement information on the prefabricated components of prefabricated buildings has not yet been completed. In addition, the code can be improved in future research to realize the fully automatic mapping transformation of BIM information into ontology instances and instance attributes. In addition, the intelligent management system of prefabricated building risks developed in the current study is only suitable for the design and construction stages. Further expansion is required for its application to the stages of component production and maintenance.

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