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Developing A Rule-Based Dynamic Safety Checking Method for Enhancing Construction Safety

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Abstract: Safety code compliance checking before construction is a key step in risk control. However, the conventional safety compliance checking methods are static model-oriented, which can lead to both the low adaptability of the model to the dynamic construction process, and low checking efficiency. This paper develops a dynamic safety checking method based on BIM and topology for enhancing construction safety management, by incorporating actual construction processes. Firstly, based on the four stages of automatic safety checking, a comprehensive dynamic safety checking framework is proposed. Secondly, the object attributes and spatial location in the BIM model are extracted to form a dynamic topological relationship database. Following this, the dynamic safety checking method is designed, and the checking results are intuitively reported to users based on BIM software. An actual construction scenery is taken as an example to verify the feasibility of the method in the final stage. The results showed that the dynamic safety checking method, based on topology and rules, can help to accurately identify safety risks in the pre-construction stage and reduce the safety risks due to poor design considerations or construction process modification.

Keywords: construction safety; dynamic checking; rule-based checking; topology; BIM

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1. Introduction

Construction is a labor-intensive industry with a high accident rate. Considering China as an example, according to statistics from 2019, there were 773 housing and municipal engineering safety accidents, and 904 deaths; compared with statistics from 2018, this is an increase of 5.31% and 7.62%, respectively [1]. In addition to the complex process and high labor intensity of the construction stage, the lack of safety checking in safety design is also a key factor in the deterioration of this situation [2]. Evidence showed that in the pre-construction stage, design for safety (DFS) can greatly reduce the likelihood of workers being exposed to risky situations in the actual construction environment [3]. A sound construction safety checking method is a key guarantee for controlling engineering risks and improving safety performance on site.

Construction safety risk control includes risk identification, risk analysis, and risk assessment [4]. Safety checking, as the basis of risk identification, plays a key role in safety risk control. However, in the face of increasingly complex building forms, it is impossible to solve complex construction safety checking problems by relying purely on static and redundant safety code texts and personnel experience [5]. One solution is provided by computer-aided construction safety checking. The existing research in this area has been applied in practice with good results. However, the checking results have a limited guiding effect on construction safety due to the separation from specific construction processes, while the daily progress and environment of construction sites are constantly changing [3,6,7]; others have made several attempts in the integration of construction processes and safety checking, with good results. Most of these studies are carried out following the logical construction process of a construction project (that is, to build the first floor first, then the second floor, etc.), and lack the consideration of specific construction procedures (such as formwork, scaffolding, etc.) [8]. The interplay between the preceding and following processes in construction can lead to constant changes regarding safety hazards. Therefore, one of the research objectives of this study is to establish a dynamic safety checking framework informatization construction, based on the actual construction process and information technology.

Arguably, the application of information technology will inevitably trigger data explosion and low execution efficiency [9]. The integration of actual construction processes with safety checking will lead to the accentuation of such problems. At present, the mainstream methods of computer-aided safety checking can be divided into BIM-based, semantic-based, and other methods. BIM-based methods are now widely used because of their advantages in information collection, transmission, and processing. One of the key reasons is provided by the Industry Foundation Classes (IFC) standard. As a standard expression channel for BIM models, IFC provides a common means with which to collaborate and to communicate information. However, this requires a clear implementation definition [6,10], and suffers from inefficient safety checking and wasted computational resources. Topology technology provides a better way to solve the problem of a large amount of data in a BIM model. Based on this, the complex building entities and attributes in BIM models are simplified into a point, and the relationship between entities or attributes is transformed into a line, which is converted into a graph database for storage with a great improvement in efficiency [11]. This approach allows the user to check the safety compliance of individual construction phases and local construction areas without detaching from the whole. This will help to reduce the data dimensionality and improve the efficiency of safety checking. Therefore, another research objective of this paper is to explore methods to improve the efficiency of dynamic safety checking based on BIM and dynamic topology network technology.

In general, this paper proposes a dynamic checking method for construction safety based on topology and rules. The hazards of construction tasks and construction processes are obtained through job safety analysis (JSA). On this basis, the key items of construction safety checking are identified. A structured generic expression based on Chinese specifications is then studied. Following this, the topological relationship of the components in the BIM model is extracted, and the rule execution path and algorithm are developed. Finally, the commercial BIM software is redeveloped for automatic safety checking. It is then verified by a four-floor office concrete building to eliminate the risk in the design stage, under the premise of ensuring the checking efficiency. The scope of this paper includes the safety checking at the design stage of the construction scheme.

The main sections of this study are arranged as follows. In Section 2, the current research progress related to automatic safety checking is introduced and summarized. Section 3 describes the method and framework of automatic safety checking based on topology and rules, including the main framework of this study which consists of four stages: rule translation, model preparation, rule execution, and result report. The main process of each part is described in detail in Section 4. The results, contributions, and limitations of this study are presented in the last section.

2. Related Research Review

BIM has great advantages over traditional methods for safety management; this is helpful for the collection, transmission, processing, and storage management of safety information [12]. By utilizing BIM software and its API, users are offered the opportunity to extend BIM applications according to their actual needs [10], such as providing useful support for developing a safety checking system for building design and construction. By using BIM technology, potential hazards can be automatically identified, and corresponding prevention methods may be applied using an automated approach [13]. By building the information model as the risk recognition platform, Li et al. [14] further proposed a Safety Risk Identification System (SRIS) and a Safety Risk Early Warning System (SREWS) for China's metro construction. Zou et al. [15] also utilized Building Information Modelling and BIM-related tools to assist in early risk identification, accident prevention, risk communication, etc.

However, construction safety management in most sites continues to rely on traditional safety checking methods, which are based on a manual, independent review with static text or form-checking tools [6,16]. Although those methods have good applicability in the checking of significant safety design defects, the disadvantages are also obvious. Firstly, comprehensive expertise and rich experience is key to achieving efficient safety checking. The subjective opinions of experts may lead to omissions, and even the tendency to commit an error in safety checking, due to the inability to simulate complex situations [7]. Secondly, the written static safety identification results are not conducive to the transmission of safety information [17]. Finally, the risk obtained by the safety checking method based on historical accidents is lagging and not conducive to the prior management of construction safety.

Due to the shortcomings of traditional safety checking methods, automatic or semi-automatic methods have emerged. The automatic safety checking method frees experts from the tedious text and improves the accuracy and efficiency of checking through 3D/4D models, ontological language, and even knowledge maps through computers. In terms of automatic methods, Singapore, a pioneer in research and application [18], began to study automatic checking, based on 2D plan drawings in 1995. In 1998, Singapore developed the CORENET system based on IFC [19]. Following this, Norway (2004), Australia (2006), and the United States (2007) successively developed their building automatic rule checking systems [18]. In recent years, due to the rapid development of various construction disciplines, professional, automatic safety checking systems for fire protection systems [20], water supply systems [21], air duct systems [22], and green buildings [23] have emerged.

The previous automatic safety checking methods may be divided into two categories: single and comprehensive methods. Single methods include BIM-based, ontology-based, and semantic-based checking methods. The comprehensive checking method is a combination of two or more single methods. In order to improve the safety design in the project planning stage, Zhang et al. proposed a BIM-based safety planning model for potential fall risks [7]. This paper integrated the construction schedule into the 3D BIM model to form a 4D safety checking framework, which plays an important role in extending traditional safety management practices and automatic safety checking. The ontology-based method is also considered a promising safety checking technology. Lu et al. proposed an ontology-based automatic checking method for construction safety for the first time, and realized the automatic checking regulations based on the JESS platform [24]. Macit et al. developed a code representation model of construction rules using the four-level representation paradigm, which enabled automatic checking in a computable form [25]. Furthermore, the practicability of this method was verified by Izmir Municipality Housing and Zoning Code. However, these single methods inevitably performed poorly in some places. Therefore, comprehensive checking methods that take advantage of complementary methods can often have better practical results. Zhong et al. researched the mismatch between the data from different sources among different stakeholders [26]. The building information in BIM, and the environmental information collected by sensors, were ontological instances, and SPARQL conversion rules were used to transform regulation clauses.

The widely-accepted method for dividing automatic safety checking stages was proposed by Eastman, who divided automatic safety checking into four stages [18]. Some studies have pointed out that safety correction should also be a part of safety checking [6]; as a result of safety checking, this study includes it in the result reporting stage by proposing preventive measures.

- Rule interpretation: This mainly transforms the current unstructured, non-text laws or regulations into a form that can be processed by computers [18]. The whole process of construction is bound by a variety of regulations and standards to ensure construction quality and prevent safety accidents [27]. However, these safety rules are usually stored in natural language, which is extremely unfavorable for computers. Therefore, the purpose of this step is to provide checking support in a language that computers can understand.

- Model preparation: As an important carrier of architectural data in the design stage, the model contains a variety of information such as the attributes of objects, the relationships between objects, etc. Building regulations usually specify this information in detail. Therefore, it is a key task in the automatic rule checking process to establish a conforming model according to construction regulations. For example, the LOD 300 level includes information such as the size, shape, and location of the object. This accuracy is considered to be in line with the fineness of general building safety checking [28]. For machinery, piping, or decoration engineering, more information needs to be provided.
- Rule execution: In this stage, the translated construction rules are matched with the information model and identifies possible unsafe conditions based on the requirements.
- Checking results reporting: The results of the automatic safety check can be reported in the form of pictures, tables, or text. Some necessary safety checking results include objects, checking results, and checking basis [10].

3. Research Framework

Based on the above analysis, the research framework and main content of this study are shown in Figure 1. The framework is based on the traditional four stages of automatic safety checking and the integrated project schedule management methods, which provide a basis for construction dynamic safety checking.

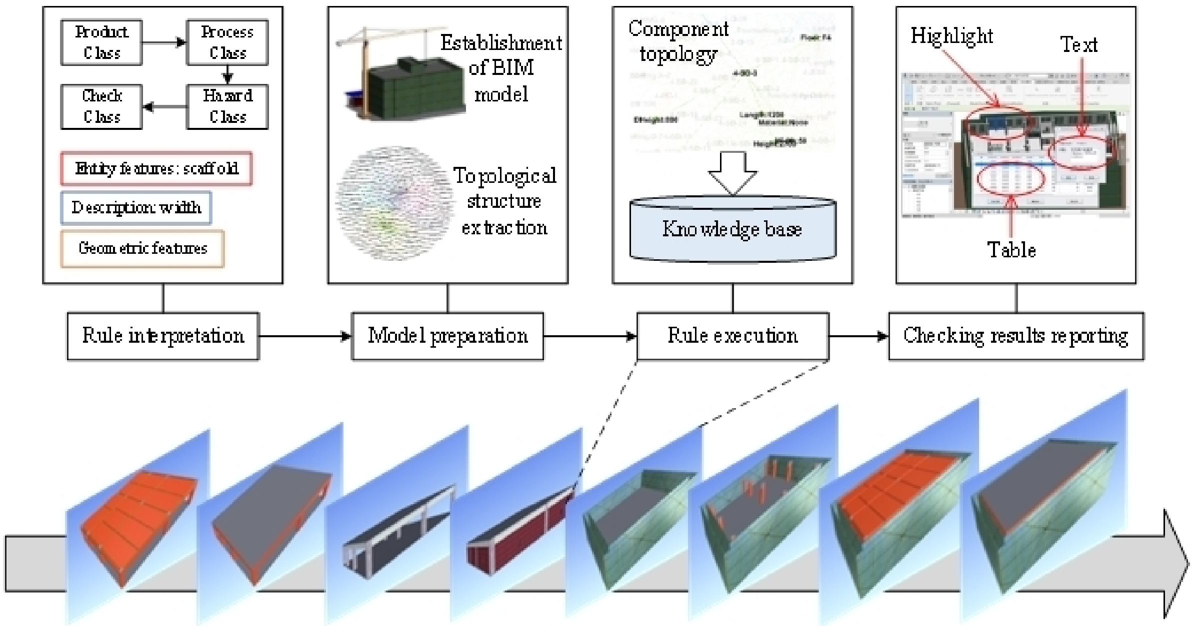

Figure 1. Research framework.

The first stage is rule interpretation. According to the specific process steps of a construction task, the checking focus of each step is determined. By systematically reading building codes, and analyzing the language structure and the description rules of the code, the general expression of the safety code is obtained, and the code expressed in natural language is transformed into a format that can be understood by computers.

Following this, the BIM model is transformed into a network diagram for storage through the topology. The topological relationship between BIM elements can be divided into three categories: impact, connection, and contain. The elements extracted from BIM model are simplified as points in the graph, and the relationships between elements are simplified as connecting lines, as shown in Figure 2.

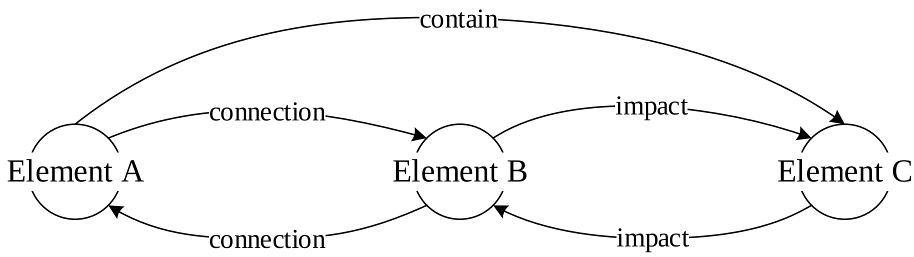

Figure 2. Topological relationship between BIM elements.

The third step is to build the knowledge base by integrating both the safety checking rules and the topological BIM elements, as shown in Figure 3. This can complete the safety rule check by executing SQL language. When the rules are executed, the required information is searched directly from the network diagram and matched with the specification expression to obtain the final results.

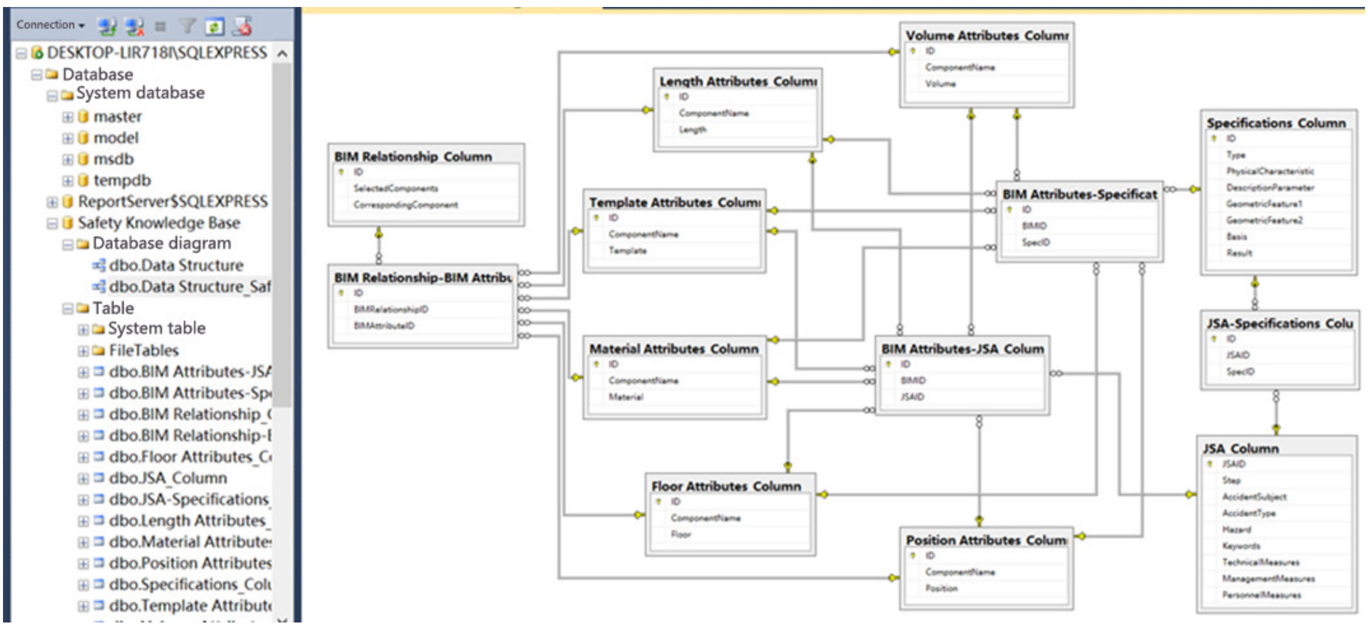

Figure 3. Knowledge base integrating both safety rules and topological BIM elements.

Finally, the components that conflict with specifications will be displayed visually, and the safety checklist and text will be generated at the same time. With regard to scope, this study focuses on the safety analysis of overall construction stages, and the detailed construction processes in each stage are not considered.

4. Topology and Rule-Based Dynamic Safety Checking System

4.1. Understanding of Construction Process and Rules

This section commences from two parts: the decomposition of work tasks and the understanding of safety regulations. Task decomposition is the logical analysis of a specific construction stage, which helps to determine the key checking points in detailed safety planning. The understanding of safety regulations is the basis that ensures the accuracy of checking in the construction design stage.

4.1.1. Task Decomposition

The influence of the construction process on safety is explored through task decomposition. Due to the different safety control rules under different procedures, it is necessary to divide specific safety checking items for different construction processes. This not only helps to clarify the key points of safety checking in each stage, but also helps to improve the efficiency of safety checking. Based on the idea of ontology, Zhang et al. standardized building safety planning knowledge into three classes, namely product, process, and safety class [29]. Under this framework, this paper further subdivides the safety class into hazard class and checking class to determine the key points.

- Product Class: refers to the engineering objects involved in the construction process, which are embodied as various graphic element components in BIM models. Depending on the construction stage, the graphic elements in the Product Class will change accordingly.
- Process Class: refers to the specific construction process. A more comprehensive list of safety hazards can be obtained by decomposing the process flow in the product class. For example, the process of formwork erection can be divided into formwork erection, fixation, and removal.
- Hazard Class: refers to the hazards existing in each construction process.
- Checking Class: safety checking is carried out based on safety hazard analysis. According to different safety hazards, the corresponding safety checking items are proposed. For example, when the scaffold is erected, the location information, geometric information, and influence range information of the scaffold shall be checked according to the hazards it may cause.

This article takes concrete structure construction as an example, decomposes the work tasks in the construction process, and carries out the process safety analysis based on the JSA method. Therefore, according to the main process of concrete structure construction, the work task product category is divided into four sub-items: formwork engineering, scaffold engineering, concrete engineering, and infill wall engineering. The workflow of each sub-item is then analyzed.

The four construction sub-items are decomposed by the JSA. Risk sources of each construction process are identified, including unreasonable component position, unreasonable component size, no safety protection devices, unreasonable protection device size, space cross operation, and other risks. The focus of safety checking is analyzed based on the identified hazards. The Sankey diagram is used to show the relationship between product class, process class, hazard class, and checking class, as shown in Figure 4. Finally, the JSA results are stored to establish a JSA database (JSAD).

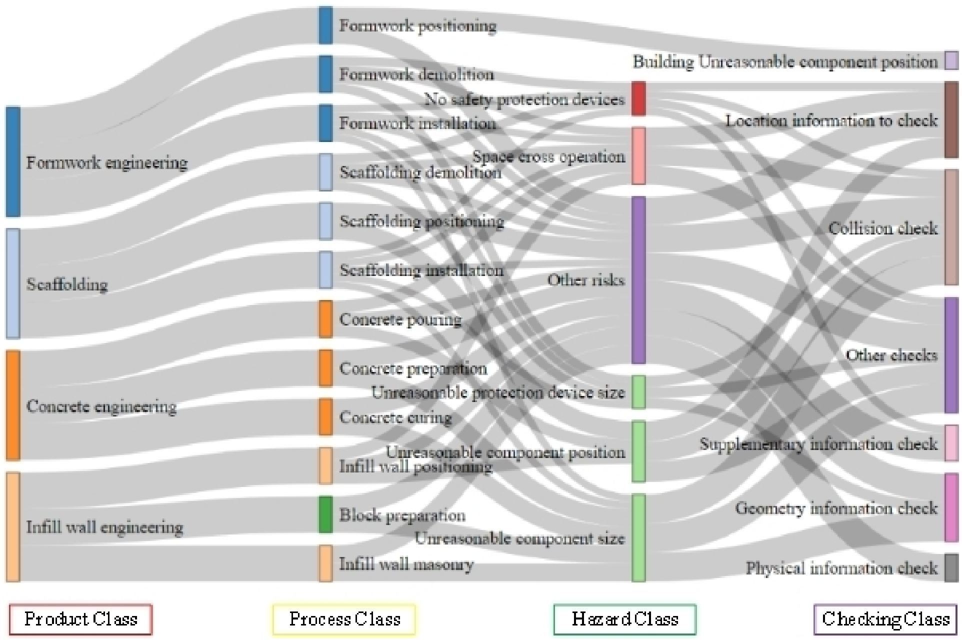

Figure 4. Task breakdown and checking items.

4.1.2. General Knowledge Expression of Rules

Construction safety codes are benchmarks to ensure the quality and quantity of a project, and this plays a guiding role in the construction process. Construction safety codes can be regarded as a standard description of theory, knowledge, and experience from actual construction processes. This paper manually screens and analyzes 21 Chinese industry standards, including the "Unified standard for safety of scaffold in construction", "Technical code for safety of forms in construction", etc.

However, rules are often formulated with a certain clear and unique expression to avoid engineering disputes caused by unclear expression. Although different codes have different emphases and means of expression, inherent rules are to be followed. This article begins with the text composition of construction regulations, considers words as the basic unit, and regards the clauses as a collection of various key elements. According to different functions, the words involved in the clauses are divided into seven categories: type, entity parameter, description parameter, comparison word, geometric feature, control measure, and control level, as shown in Equation (1):

$$\begin{gathered}\text{Rule} = \{\text{Types: (first-level, second-level), Entity, Description,} \\ \text{Comparison, Geometric, Measure, Grade: (I, II, III, IV)}\}\end{gathered} \tag{1}$$

Among them, the type is the constraint object of this specification, which is divided into first-level and second-level types. In this article, the first-level category is the main constrained object in the normative clauses. The second-level category is the related constrained component of the first-level category. Entity parameters, description parameters, comparison words, and geometric features are the main control items of engineering, which specify the geometric features of objects or attributes. Among them, comparison words are usually reflected in the control of object geometric features, which are important constraints on entity parameters. Control measures are supplementary provisions for the safety protection of the objects in clauses. Moreover, these clauses follow a common expression in terms, as shown in Table 1. This expression is helpful to divide the reasonable importance of safety checking results. Furthermore, not all the normative provisions can extract the above seven types of information, and the missing information is directly replaced by null, as shown in Table 2.

Table 1. Description of control level.

Standard Terms	Control Level	Rule Grade
"Must", "Forbidden"	Very strict: it must be done	I
"Shall", "Shall not"	Strict: this should be done under normal circumstances	II
"Suitable", "Not suitable"	Allows a little choice, which should be done first when conditions permit	III
"Can"	There is a choice: it can be done under certain conditions	IV

The structural codes are stored in the knowledge base based on the expression. It should be noted that the knowledge base is mainly aimed at the provisions in the specification that can be standardized according to Equation (1). Many clauses cannot be expressed by general expressions, which are mostly abstract objects and difficult to be embodied by models. For example, clause 8.3.1 of GB 51210-2016 requires that "the spacing and step distance of supporting scaffold shall be determined according to the design calculation". Although the "design calculation" here can be placed in the control item in the general expression, it is difficult to specify this in a BIM model. Finally, the SQL server is used to establish a rule knowledge base (RKD) for storage.

Table 2. Examples for general knowledge expression of rules.

Clause	First-Level, Second-Level	First-Level, Second-Level	Entity	Description	Comparison	Geometry	Control Measures
When edge operation is carried out at the height of 2 m or above, protective railings shall be set at the empty side and closed with fine mesh safety vertical net or tool-type board.	Scaffolding, templates	Edge	NULL	NULL	≥	2.0 m	With guard railings, safety nets, or railings
When the short side length of a non-vertical hole is greater than or equal to 1500 mm, protective railings with a height of not less than 1.2 m shall be set at the working side of the opening, and the hole shall be closed with safety net.	Scaffolding, templates	Non-vertical hole	NULL	Shortest side length	≥	1.5 m	With guard railings, safety nets
	NULL	Non-vertical hole	Guard railings	Height	≥	1.2 m	NULL

4.2. Component Topology Graphs

This study builds a component topology graph (CTG) to optimize and visualize the chaotic object attributes and relationships. Compared with the traditional database, the intuitive representation method of component entities and their attributes is helpful to express the dependency relationship between components and attributes. Users or developers can obtain structured query results without mastering complex query language or the database paradigm.

The CTG consists of two parts: one is a component topology graph of attributes (A-CTG); the other is a component topology graph of relationship (R-CTG). Both parts take the components in BIM models as the minimum unit. The component and its attributes are nodes in the A-CTG, and their affiliations are edges. In the R-CTG, the components are regarded as nodes, and the relationships between them are regarded as edges, as shown in Equations (2)–(4).

$$G = (N(G), E(G)) \tag{2}$$

$$N(G) = \{v_1, v_2, v_3, \cdots, v_i\} \tag{3}$$

$$E(G) = \{e_1, e_2, e_3, \cdots, e_j\} \tag{4}$$

where $N(G)$ is the finite set of components or attributes, i is the number of components or attributes in the finite set, v_i is the specific component attribute node. $E(G)$ is a finite set of relationships between nodes. Where $e_j = (v_m, v_n)$, $1 \leq m, n \leq j$, $m \leq n$, e is the edge of node v_m and v_n, j is the number of edges in finite set $E(G)$. $e_j = 0$ indicates that there is no association between two nodes; $e_j = 1$, there is association between two nodes.

4.2.1. Component Attribute Topology

The A-CTG is the graphic combination of component entities and their attributes in a BIM model. Component entities signify building components (such as beams, columns, floors, walls, stairs, etc.), and other accessory components (such as openings, railings, etc.). According to different categories, the entity attributes are divided into basic information (element ID), geometric information (length, volume, area, spatial relationship, etc.), physical information (performance, material, quantity, weight, etc.), location information (relative position of construction), and affiliated information (including the scaffold and template attached to the component). Considering a model element as an example, the component entity and component attributes are extracted, as shown in Table 3. The component attributes are extracted from the model by Dynamo in a visual programming way, as shown in Figure 5.

Table 3. Component entity and its attribute information extraction.

Component Information	Basic Information		Geometric Information		Physical Information	Location Information	Affiliated Information	
	Name	ID	Size	Height	Material	Location	Scaffold (Y/N)	Framework (Y/N)
Parameters	1-Z-1	393301	400×400	3000	concrete	A-1	Y	Y

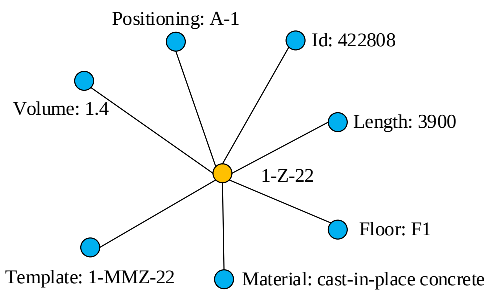

Figure 5. Example of A-CTG.

4.2.2. Component Relationship Topology

Dynamo is used to extract the components from the BIM model to form the R-CTG. The relationship between two components is often stipulated directly or indirectly in codes. For example, scaffolding that exceeds 3 m must be set up with formwork in the specification. In order to extract the correlation from the BIM model, the following steps are carried out, as shown in Figure 6. Firstly, the components are filtered according to their positions. Then, the bounding box is used to judge whether the adjacent elements in the geometric space intersect. Finally, the self-intersecting and repeatedly intersecting elements are deleted. The remaining information is stored in the exported file and form an R-CTG, as shown in Figure 7.

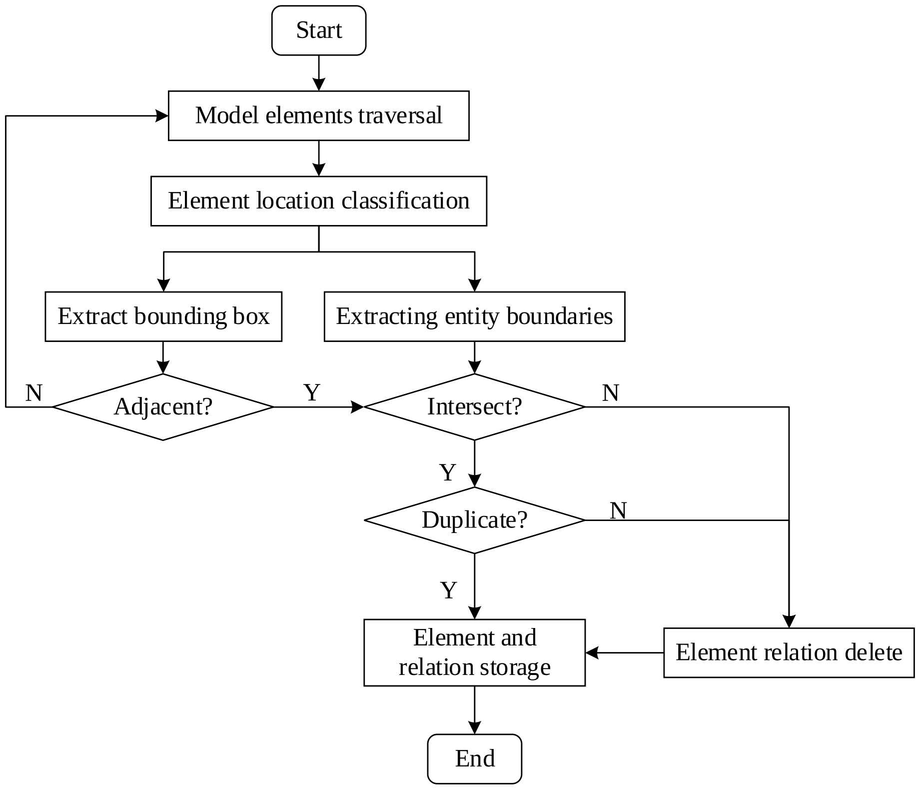

Figure 6. Entities' relationship extraction process in BIM model.

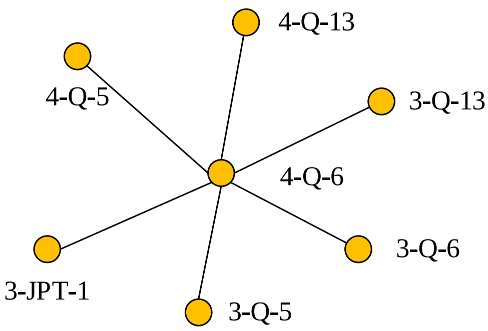

Figure 7. Example of R-CTG.

4.2.3. Topological Relationship Database

The A-CTG and R-CTG extracted from the BIM model are combined to form a dynamic topological relationship database (DTRD). In the database, all entities are regarded as nodes, including components and their attributes. The relationship between entities is regarded as an edge, and the graph composed of nodes and edges forms a topological graph. The topological graph represents the position relationship between the nodes. The shape, size, and distance of the entity have no relationship with the node distribution.

In a computer network, the topology can be classified into six types: bus, star, ring, tree, mesh, and hybrid topologies [30]. The star topology usually has a central node, and other sub-nodes are connected with a central node through the edges to form a radial shape. In the mesh topology, any node can be connected to form a network shape [30]. The component topological relationship of the BIM model includes the component attribute relationship and the component-to-component relationship. The topological graph of a single component can be represented by star topology, and the relationship between components can be represented by mesh topology. Therefore, the topological relationship of BIM components is described and stored by star/mesh hybrid topological structure, as shown in Figure 8.

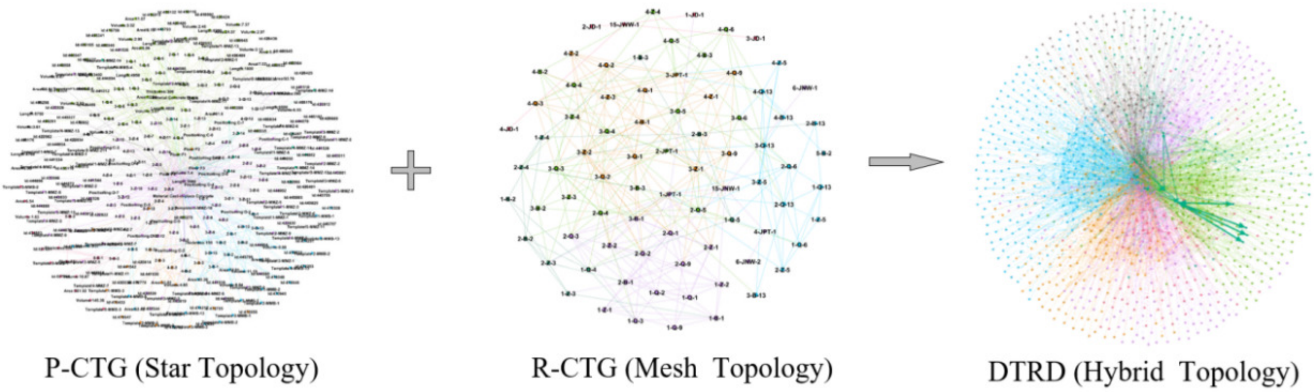

Figure 8. Construction process of DTRD.

The data of component attributes and the relationship between components extracted from Dynamo are imported into Gephi to form a DTRD. The DTRD can display the attributes of each component and the relationships between components, and then dynamically filter and screen the related components in specific scenarios, providing a data basis for dynamic construction safety checking combined with the construction process.

The DTRD can be dynamically extracted according to the construction process. Considering the first-floor construction of a concrete structure as an example, the construction process mainly includes three processes: formwork engineering, concrete engineering, and infill wall engineering, among which the former and latter processes may have mutual influence. Therefore, the BIM model based on the construction process is established first. Following this, the topological relationship among components in each stage is extracted dynamically to form a DTRD, and the safety code compliance checking is conducted based on this. On the one hand, the checking method combines the specific construction process, which is in line with the actual construction logic. On the other hand, compared with the traditional database traversal retrieval method, it has the advantage of search efficiency.

4.3. Rule Execution Process Design

The rule execution method is established by designing the collaborative mechanism between databases through the process design. In this study, the rule execution mechanism is established via three aspects of the dynamic safety checking process, path, and algorithm design. The process design is divided into a preliminary design and a detailed design, which are expressed by Business Process Modeling Notation (BPMN). The path design clarifies the relationship among the three databases (JSAD, RKD, and DTRD). Finally, the path is programmed by designing the rule execution algorithm.

Figure 9 shows the dynamic safety checking process based on topology and rules. To improve the dynamic and comprehensive process of safety checking, safety planning was divided into overall checking and the dynamic checking process; overall checking does not involve specific construction processes but checks the established complete BIM model directly. Dynamic checking is carried out in combination with specific construction processes. The overall process of safety checking includes rule interpretation, model preparation, rule execution, and result report.

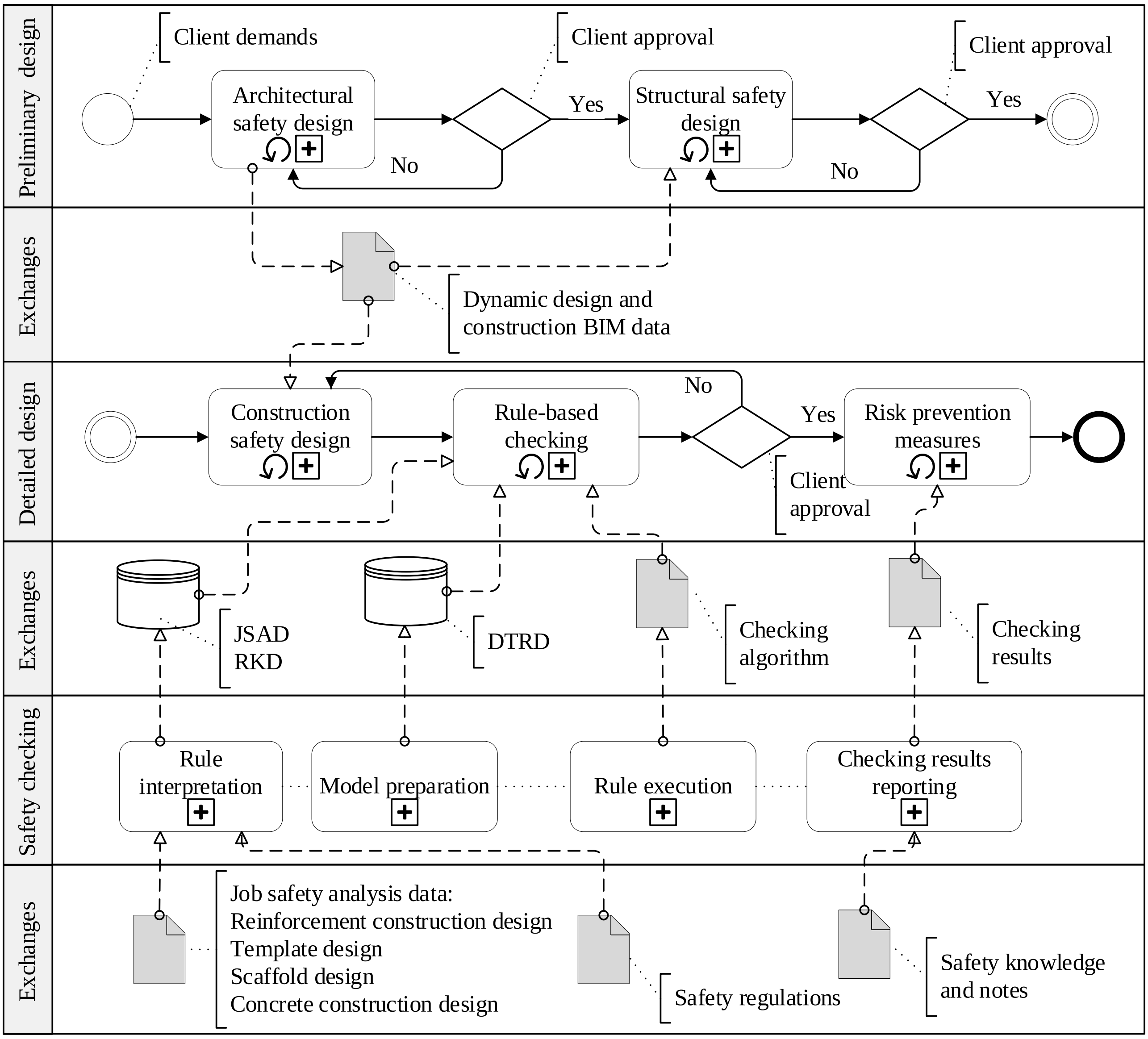

Figure 9. The dynamic safety checking process.

Two different checking paths are designed in this study, including the direct checking path of the DTRD and the RKD, and the rule checking path, as shown in Figure 10. These safety checking paths based on the DTRD-(JSAD)-RKD performing safety checking tasks dynamically according to the user's requirements. Among them, query line 1 (DTRD-RKD) detects safety design defects by checking the complete BIM model directly, which is suitable for the overall checking process. This allows users to check the general safety risk items in the construction design scheme. Query line 2 (DTRD-JSAD-RKD) detects the safety checking path designed for dynamic checking, which is suitable for special construction safety detailed design. Under this path, the DTRD of different process stages is selected based on the JSAD first. Then, it matches with the RKD and outputs the safety checking results combined with the construction process.

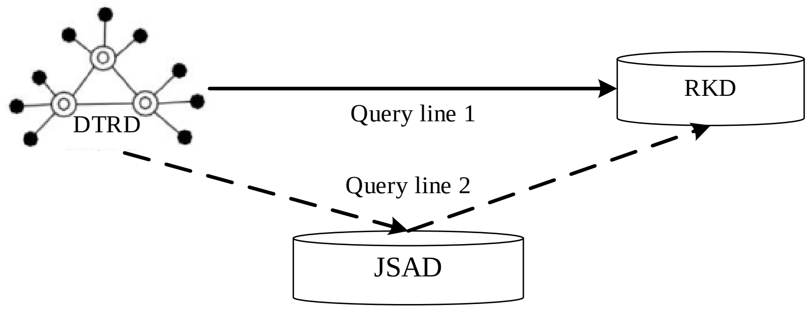

Figure 10. Query lines of dynamic safety checking.

Figure 11 shows a workflow of the dynamic safety checking algorithm. According to the query lines, the algorithm first determines the specific checking process dynamically according to the client's demands. If the selected process is overall checking, the algorithm is executed according to line 1; otherwise, the algorithm is executed according to line 2. In the overall checking process, the DTRD is directly extracted from the current BIM model and matched with the RKD. In the dynamic checking process, the model is first matched with the actual construction process of the project, then the JSA-DTRD is generated. Component groups are extracted separately according to procedures, and their safety compliance is checked. Finally, the current component is judged. If the current component check results are all safe, the above process will be repeated; otherwise, according to the safety checking results, the BIM model will be returned to visualize the unsafe components and output the checking report.

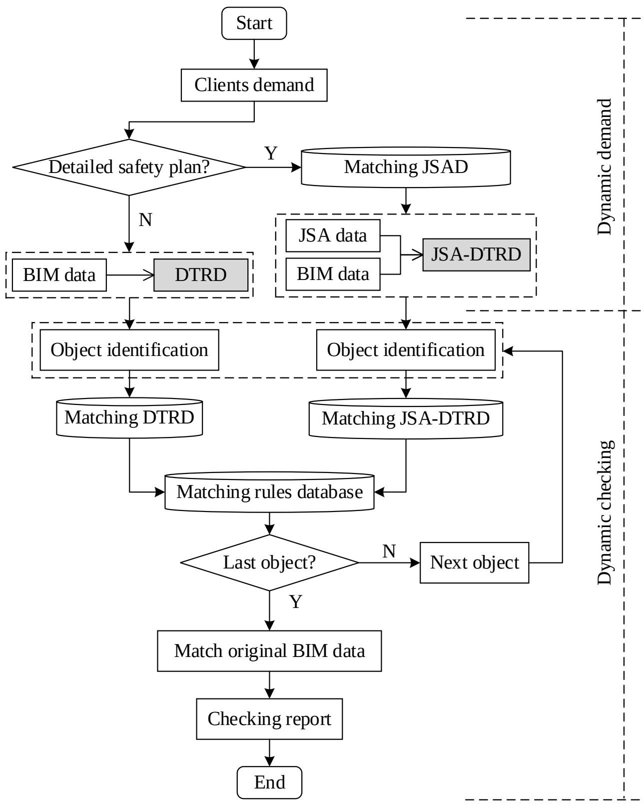

Figure 11. Algorithm of dynamic safety checking.

4.4. Dynamic Safety Checking System Development

A dynamic safety checking system is established through the secondary development of the commercial BIM software Revit. According to the designed checking process, path, and algorithm, the basic framework of the system is designed. The system design tools include Revit (original model), SQL severe (database), and several application programming interfaces (APIs). The designed dynamic checking system includes three modules: the information management module, the rule execution module, and the result report module. The main functions of the information management module include storage of construction procedures, specifications, the DTRD, etc. This module is the basis of dynamic safety checking. The rule execution module integrates the designed checking path and algorithm into the checking process, which is the core module of the system. The final report module explains the safety checking results in the form of text, tables, and pictures. This reporting method considers the friendliness of the graphical interface for intuitive understanding, and the advantages of the detailed description of the static text. The developed dynamic safety checking system allows users to check the complete safety design according to their needs directly, and can also be used for the checking of sub-items in the construction process only.

5. Validation

This research aims to propose a construction safety dynamic checking method that matches the actual construction process. A four-story concrete structure office building is used to verify the construction dynamic safety checking method proposed in this article. Firstly, a simulated dynamic BIM with actual construction processes is established. In the model preparation, the main structure is built using Revit software, and the temporary facilities are automatically generated using the modeling master (construction) software developed by Hongwa Technology Company [31]. The overall construction PERT of this office building is shown in Figure 12. The component attributes and topological relations between components can be extracted through Dynamo, and the topological network can display the attributes of each component and its associated components. Taking the vertical hole 4-SD-3 as an example, the topological network can display the height, length, position, and other attributes of this component, while its related components are only the wall 4-Q-2, as shown in Figure 13. However, according to the specification, if the short side length of the vertical hole is not less than 500 mm, protective railings shall be set at the free side. Because the associated railings are not found, the safety checking result will show that it is unsafe.

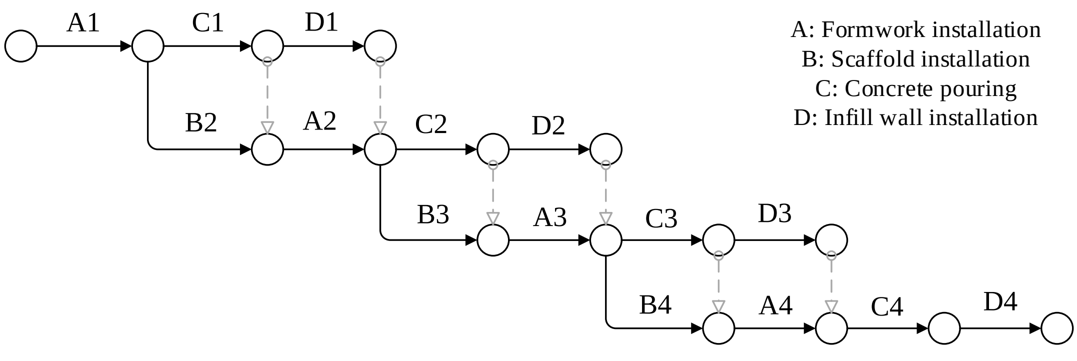

Figure 12. Overall construction PERT of the building (The number indicates which layer it is).

Taking the construction of the fourth-floor structure as an example, according to the component ID, the application will compare the information with the established database in advance, extract the related component information based on the JSA-DTRD, and match the information with specifications in the RKD to obtain the checking results, including "safe" and "unsafe" components. The components whose results are "unsafe" are filtered, and all non-conforming component information and specification references are obtained, and the results are output in the form of a dialog box, as shown in Figure 14.

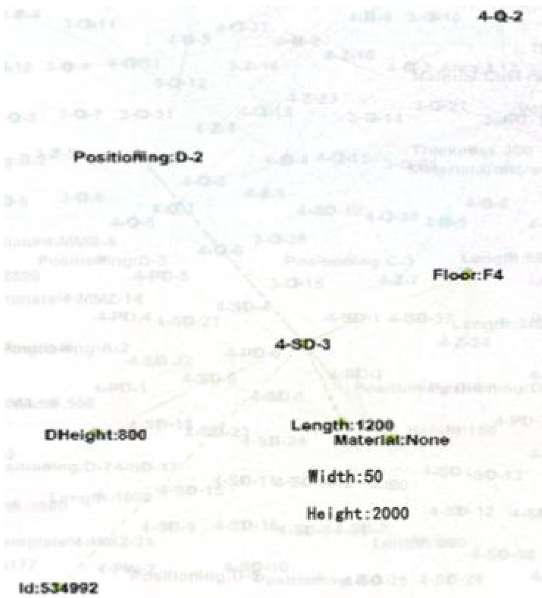

Figure 13. Topology relationship of 4-SD-3.

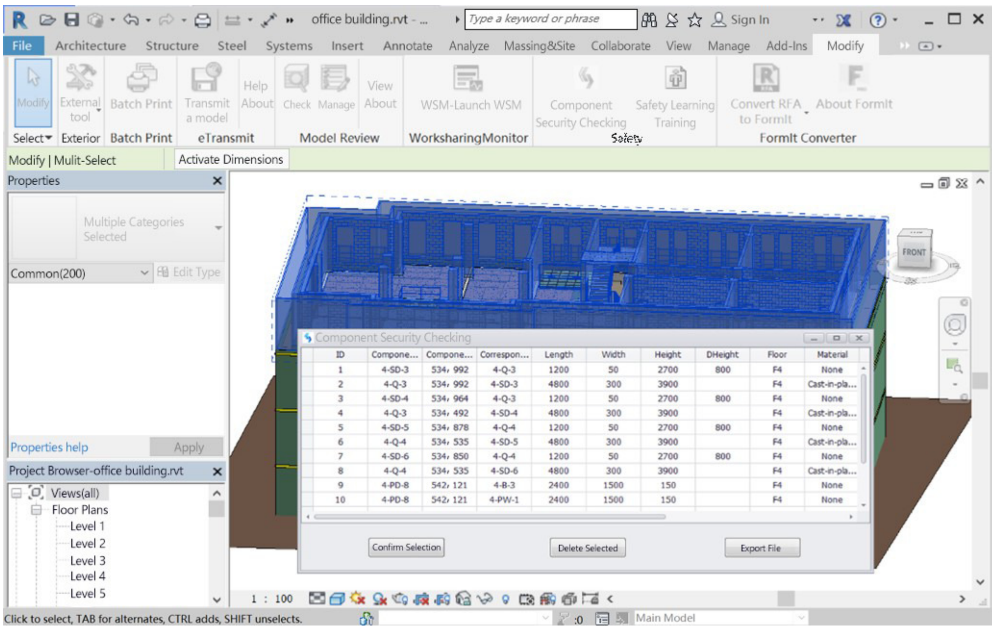

Figure 14. Safety checking results.

The specific safety checking results are output in the form of a dialog box. The information displayed in the dialog box mainly includes the name of the unsafe component, the component ID in Revit, the associated components, the attribute, and reference specification clauses. The component can be selected through the pop-up result dialog box to display the checking information of the selected component and automatic positioning, as shown in Figure 15, which is convenient for safety managers to locate and to investigate unsafe components and take measures.

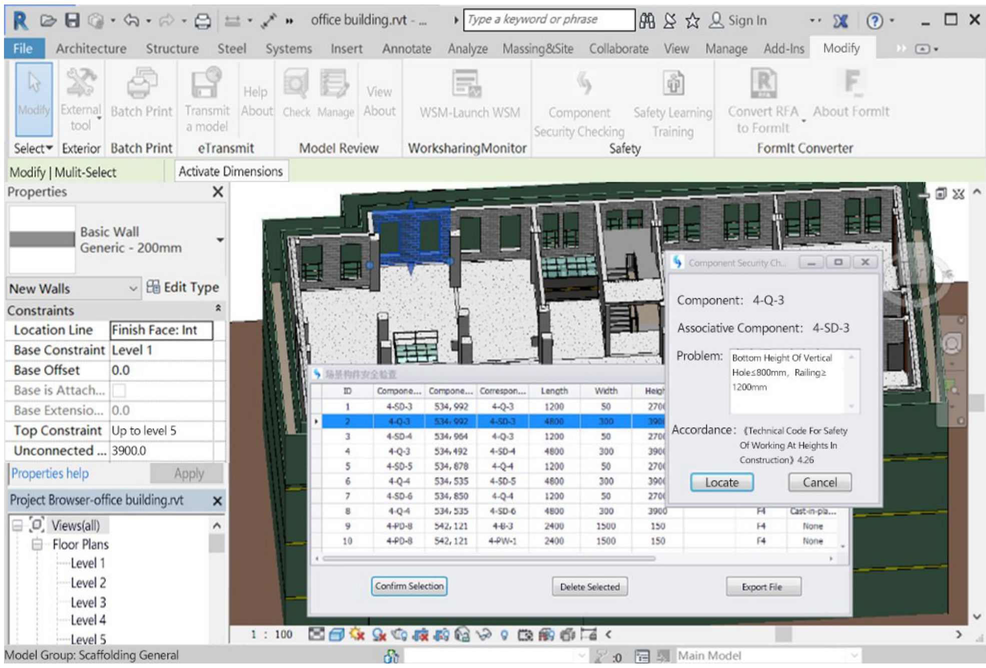

Figure 15. Visualization of the checking result.

6. Discussions and Conclusions

This study proposes a construction dynamic safety checking method and framework based on topology and rules. The complex relationship formed by the interaction of the front and back procedures during construction can easily result in safety hazards. The dynamic safety checking framework developed in this article extracts the DTRD according to the actual process, and uses it as the basic unit to detect construction safety defects. The empirical results prove that the construction dynamic safety checking framework proposed in this paper can be used for dynamic safety design. The visualized dynamic topological relationship helps to provide an understanding of the influential relationship between components intuitively, and improves the speed of safety checking. The JSAD reduces the dimensionality of the DTRD, and can significantly improve checking efficiency. Additionally, the method of safety checking reporting using intuitive visual images and detailed table texts also plays a positive role in the transmission of construction safety information. Theoretically, the construction dynamic safety checking method designed in this study enriches the rule-based safety checking method. Topology-based component representation also provides new insights for improving checking efficiency. In practice, this study provides support for construction stakeholders to reasonably review the safety defects in the construction process and improve construction safety from the perspective of design. Moreover, this method is suitable for construction safety planning of other similar projects, except for construction projects such as underground engineering, protection engineering, and even offshore construction engineering.

The research contributions of this article are discussed to clarify the significance for further research. First, the method proposed in this paper provides a new approach for the dynamic checking of construction safety. Previous studies have done less work on safety checking in combination with actual construction procedures. As an argument for dynamic safety checking, this study puts forward a new construction safety dynamic checking method and implementation framework based on the DTRD-(JSAD)-RKD. Secondly, a flexible construction safety checking method based on the topological relationship is proposed, which reduces the workload of model checking while retaining the original object attributes and relationships. Before the contractor determines the final construction scheme, it will inevitably be modified many times. If one of the processes is adjusted, the previous and subsequent processes need to be changed accordingly. This kind of change may cause unpredictable safety risks. According to the topology map, we can quickly find the impact scope of certain specific changes.

The limitations of current research are reflected via the following aspects: (1) Most of the rules are translated by hand. This may lead to the translation of specifications becoming time-consuming and laborious. Moreover, the general expressions summarized in the study are only applicable to the clauses that can be embodied by the model, which makes the generality of safety checking insufficient. (2) The research scene and practice environment are limited. Firstly, the actual construction process involves a large number of different construction procedures. To verify the feasibility of the framework, this paper only takes the concrete structure construction as an example, and studies four construction processes. Furthermore, the operations in the Process Class are limited. The selected operations are mostly the main construction tasks. Some ancillary construction tasks (such as site leveling, formwork painting, etc.) are not included. Most of these tasks are manual and are difficult for the model to directly reflect. (3) The implementation of a dynamic safety checking system creates a high demand for the BIM model. Firstly, the quality and accuracy of the BIM model directly determine the level and effect of dynamic checking. A high-quality and high-precision model can provide the system with more accurate judgment and reduce the risk of missed and false detection. Secondly, to combine construction safety checking with actual processes, the design depth of the BIM model needs to match the process depth. Therefore, it is necessary to ensure the deep integration of the construction schedule and the BIM model in safety design.

Future research can be carried out in relation to many aspects. This is firstly because the construction dynamic safety checking method is based on the analysis of process tasks. In the actual construction, the process is more complex and changeable. The process of model preparation and rule execution may change greatly. Therefore, future research could consider the dynamic safety checking framework under complex process conditions. Secondly, in the context of massive model data, developing a method for optimizing the topology structure, and improving the efficiency of component extraction, is also a problem worthy of study. The extraction of the DTRD is a key step in the proposed dynamic safety checking method and framework. The DTRD needs to extract component relationships from the BIM model through programming. This appears to be a feasible method for extracting the components within a certain range according to the object's location. Thirdly, methods for integrating the lightweight BIM platform, cloud computing, and other new technologies into the construction dynamic safety checking framework may be studied, and this is expected to greatly improve the efficiency of construction dynamic safety checking.

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