Safety Science 87 (2016) 202–213

Contents lists available at ScienceDirect

Safety Science

journal homepage: www.elsevier.com/locate/ssci

Construction risk knowledge management in BIM using ontology and semantic web technology

L.Y. Ding [a], B.T. Zhong [a,*], S. Wu [b], H.B. Luo [a]

[a] Institution of Construction Engineering Management, Huazhong Univ. of Science and Technology, Wuhan 430074, PR China
[b] Department of Architecture and 3D Design, School of Art, Design and Built Environment, University of Huddersfield, HD1 3DH, UK

ARTICLE INFO

Article history:
Received 17 June 2014
Received in revised form 3 April 2016
Accepted 9 April 2016
Available online 22 April 2016

Keywords:
Construction risk
BIM
Ontology
Semantic web technology

ABSTRACT

The development of Building Information Modelling provides a visual and information-rich environment to incorporate the construction risk knowledge in the domain of safety management. Ontology and semantic web technology offer an opportunity to enable such domain knowledge to be represented semantically. This paper attempts to take advantage of the strength of BIM, ontology and semantic web technology to establish an ontology-based methodology/framework for construction risk knowledge management in BIM environment. The risk knowledge is modelled into an ontology-based semantic network to produce a risk map, from which the interdependences between risks, risk paths can be inferred semantically. Based on the semantic retrieval mechanism, the applicable knowledge is dynamically linked to the specific objects in the BIM environment. Based on the methodology, a prototype system is developed as a tool to facilitate the construction risk knowledge management and reuse in hope of indirectly improving the construction risk analysis process. A case application is implemented to demonstrate the risk prevention through construction process/method selection, including the risk factors identification, risk paths reasoning and risk prevention plan recommendation. Finally, a questionnaire survey highlights the potential benefits and limitations on the deployment of such system.

1. Introduction

In any construction project, risk management is a very knowledge intensive process. The probable risks are identified by experts through the risk evaluation exercises based on their individual expertise and available design information (i.e. 2D construction drawings). Having identified the possible risks, relevant preventive measures can be put in place. However, it is recognised that 2D information does not effectively support risk identification because limited information is provided by 2D drawings (Li and Hua, 2012). Also, the provided information is not dynamic and only represents the project at certain stage. By comparison, Building Information Modelling (BIM) has been evidenced to substantially improve the information environment for the construction risk identification and prevention (Smith and Tardif, 2009; Kiviniemi et al., 2011). In a BIM environment, more effective and proactive construction risk and safety management can be accomplished (Ku and Mills, 2008).

Ontology is the formal conceptualization of knowledge in a certain domain (Zhang and El-Diraby, 2012). There is plenty of research discussing the use of ontologies to support semantics in the construction industry (Mutis and Raja, 2009; Svetel and Pejanovic, 2010). Ontology and semantic web technology has offered a way to semantically represent and reuse domain knowledge (Anumba et al., 2008; Elghamrawy et al., 2009). The literature review also demonstrates the advantages of BIM, ontology and semantic web technology in their own respective applications; however, there is little research in combining BIM, ontology and semantic technology for the construction risk management. Meanwhile, with the development of BIM, people come to realise that only rich information is associated with the building object models, can the value of BIM be fully reached. Even though BIM provides potential for many analysis and simulation processes which is impossible using traditional 2D design approaches, the static links of the information to the building objects models mean that once the project models or information change, the links have to be re-established again. This contributes to the dilemma between integrating more information into the building object models and the proper model size (Zhang and Xing, 2013). In fact, the information should be integrated with (linked to) the building object model in a dynamic and flexible way.

* Corresponding author at: School of Civil Engineering & Mechanics, Huazhong University of Science & Technology, Wuhan 430074, PR China.
E-mail address: dadizhong@hust.edu.cn (B.T. Zhong).

http://dx.doi.org/10.1016/j.ssci.2016.04.008
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In this context, this paper attempts to take advantage of the strength of BIM, ontology and semantic web technology to establish an ontology-based methodology for construction risk knowledge management in BIM environment, to organise, store and reuse construction risk knowledge.

The construction risk knowledge is modelled into an ontology-based semantic network to produce a risk map, from which the interactions and interdependences between risks, risk paths can be captured and inferred semantically. Based on semantic reasoning and retrieval mechanism, the applicable knowledge is dynamically linked with or recommended to the specific objects in a BIM environment. Based on the methodology, a prototype system is developed as a construction risk knowledge management tool to facilitate the knowledge reuse during the risk analysis process. A case application and a questionnaire survey are done to further show the applicability and benefits.

2. Related work

2.1. Risk knowledge model and representation

Research investigations suggested that practical risk management was often based on previous experience and knowledge (Han et al., 2008; Tserng et al., 2009) and knowledge reuse is one of the key areas in construction risk management research (Zoysa and Russell, 2003; Tah and Carr, 2001). Several risk analysis and modelling techniques, such as the Check List, Failure Mode and Effects Analysis (FMEA) tables, Hazard and Operability study (HAZOP), What–If rule, and Fault Tree Analysis (FTA) diagrams, have been developed to facilitate the risk management. A number of knowledge-based risk and safety management applications have also been developed to improve the safety performance, for example, Kamardeen (2009) developed a conceptual framework of web-based safety knowledge management system for builders; Goh and Chua (2010) proposed a case-based reasoning approach of construction hazard identification. In these applications, the risk knowledge models/schemas were developed and represented in Object-Oriented approach.

In practice, the risk checklist is mostly used as a tool to help the engineers identify potential risk factors. Some researchers classified risks into groups to manage the lists of risks via risk breakdown structure (Hillson, 2003). However, these tools exclude the causal relationships of risks. Tah and Carr (2001) demonstrated the associations between risk factors and risks using "cause-and-effect" diagrams. Dikmen et al. (2007) also pointed out the importance of independencies among risk-related factors. In many risk management system, the interdependencies are modelled in relational database system. However, in a traditional relational database, semantics relations are not explicitly expressed. It is time-consuming to represent and find the semantic of the field dependencies between the complex table structures. Any changes of the interdependence may imply recreating the interdependence network from the beginning, because of their very complex interaction structure. Therefore, it is necessary to explicitly represent interdependences among risks and risk factors semantically in a model.

2.2. Ontology and risk knowledge management

In the AEC industry, the applications and studies of ontology and semantic technology have been undertaken in risk-relevant management domain. Tserng et al. (2009) proposed the ontology-based risk management framework to enhance risk management performance. Fidan et al. (2011) proposed an ontology model to associate risk-related concepts to cost overruns, and the ontology model was then used for developing a database system. Wang and Boukamp (2011) used ontology to structure the knowledge about activities, job steps and hazards to improve access to a company's JHA (Job Hazard Analysis) knowledge, and discussed an ontological reasoning mechanism for identifying safety rules applicable to given activities. Forcada et al. (2007) applied ontology to interrelate environmental, health and safety risks. Furthermore, the ontology serves as the basis for analysing Environmental, Health and Safety risks and defining technical solutions and preventive measures. All those studies had demonstrated the potential benefits of ontology in risk management and provided the basis for this paper.

2.3. BIM for construction risk and safety issue

In last few years, a lot of work has been done on the BIM-based construction risk management and application. The research from VTT Technical Research Centre of Finland shows that BIM model can support the safety planning by adding the planned temporary site and safety arrangements to the model (Kiviniemi et al., 2011). Zhang et al. (2013), from Georgia Institute of Technology, proposed an approach to extend BIM to integrate automated hazard identification and developed an automated safety checking platform for preventing fall-related accidents. Li and Hua (2012) proposed an object library approach for managing construction safety components based on BIM, in which the knowledge related to the construction safety components, such as the safety equipment, is collected and represented for design decision in design-for-safety. These studies have proven the capability of a BIM technology on improving the safety analysis and decision making. However, the studies so far are only focused on taking advantage of the rich visualisation and information environment BIM provided for the safety management.

2.4. Integrating knowledge with BIM

There are some efforts in integrating the relevant knowledge with BIM, even though they are not focus on the construction risk domain. Fruchter et al. (2009) attempted to transform the BIM into the building knowledge model by linking the knowledge tool with BIM. Meadati and Irizarry (2010) discussed the feasibility of developing BIM as a knowledge repository by adding new parameters for knowledge resource as project parameters or shared parameters. Goedert and Meadati (2008) integrated construction process documentation into BIM. Pishdad and Beliveau (2010) integrated multi-party contracting risk management model in BIM. Calos and Soibelman (2003) described an approach to automate integration of text documents into IFC compliant model-based systems. However, they integrated the relevant information/documents via static links between the information/knowledge and the parameters of the project model. This way of coupling tightly knowledge with specific project models requires creating static links between each product and its applicable knowledge. This issue together with the advantage of ontology and semantic web technique constitutes the starting points of this research.

3. Methodology and framework

3.1. Framework

This methodology proposes a framework for managing and reusing the construction risk knowledge in the BIM environment to facilitate the construction risk analysis process, as shown in Fig. 1, which includes BIM model, ontologies, information

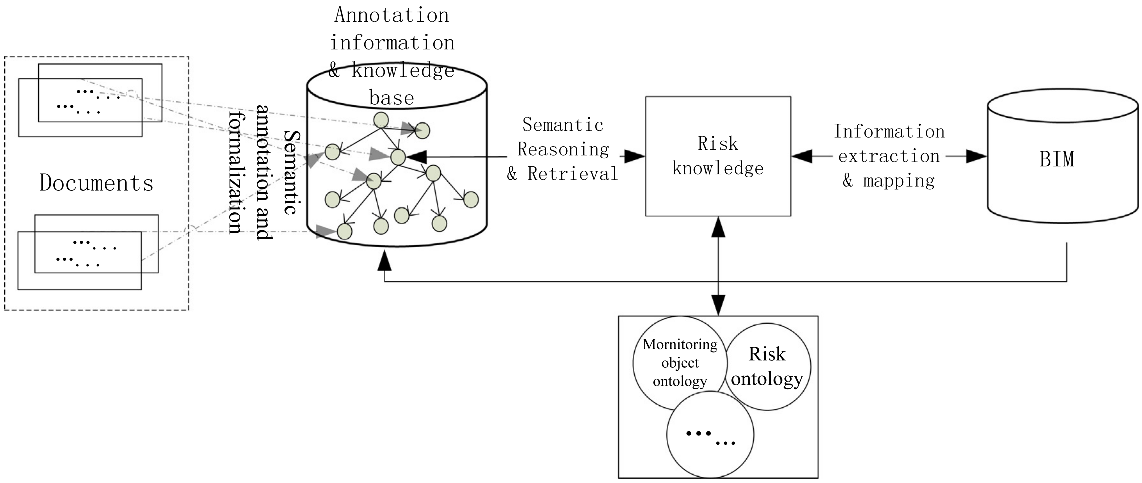

Fig. 1. The framework/methodology of this research.

extraction and mapping, risk knowledge resource and semantic annotation, semantic reasoning and retrieval.

Ontology is used to standardise the description of each aspect of risk knowledge and facilitate the knowledge reasoning and retrieval, the respective risk sub-ontologies correspond to each facet of construction risk knowledge. The construction risk knowledge is modelled and represented using ontology and semantic web technology.

Ontologies include concept taxonomies and a set of relationships (to link concepts), a set of formal axioms (to illustrate the behaviour of concepts). There are two kinds of relationship, attributive relationship and cross tree relationship. The first one is used to link an entity with its attribute. The second one is used to connect different concepts entities.

In engineering practice, most of risk knowledge is stored in paper or electric documents. These documents can be annotated semantically with the concepts/properties in the ontology. This enables the documents are organised in the structure of given ontology models, semantically retrieved and reasoned via the annotation information.

BIM model provides visual information-rich environment for the construction risk knowledge management and application. Providing the information needed for the construction risk management is available in BIM, the information can be extracted and mapped into the concepts in the ontologies, and used for the construction risk knowledge retrieval and inference. The semantic inference and retrieval mechanism enables dynamically linking the applicable construction risk knowledge to objects in BIM to facilitate the construction risk knowledge-based applications in BIM environment, which helps solve the dilemma of the between integrating more information into the building object model and the proper model size.

3.2. Knowledge reasoning

The construction risk knowledge is described in two main aspects: one is about risks including risk factors, risk rules, risk prevention measures, risk consequences and so on; the other one is about construction risk monitoring objects, which acts as the risk context, including construction product, construction method, construction resource, construction activity, construction process, etc.

The sub-ontologies provide the common vocabulary/concepts and relationships for the construction risk and their context description. This helps to overcome the lack of a common vocabulary, which results in poor, incomplete, and inconsistent communication of risks (Tah and Carr, 2001).

Some semantic relations exist between sub ontologies. For example, the causality relationships between risks and risk factors are modelled explicitly with the relation "Cause". These causality relationships form into risk causality paths. In addition, construction risks themselves are related to each other, and one risk may cause other risks, as a result, these causality paths are connected into a risk path network.

The risk monitoring objects refer to the construction elements that have potential construction risks, including construction application context information of the safety specifications. As we know, the risk management is context sensitive, different construction objects, different construction processes, construction activities and resources could imply different risks that need to be considered. Risks stem from these construction elements and the risk monitoring objects constitute the construction risk context. Wang and Boukamp (2011) used the Construction Method Model as the application context information of the safety specifications.

In this methodology, these construction elements can be modelled into respective construction risk monitoring object sub-ontologies, such as, the construction resource ontology, construction method ontology, and construction product ontology. Similarly, the risk monitoring object sub-ontologies are used to depict construction risk context in which risks/events exist. The context information facilitates the risk knowledge retrieval. The semantic relations exist between the concepts of these sub-ontologies. These semantic relations between the construction elements sub-ontologies can reference the meta model given by Zhong and Li (2014), in which, the relations among construction method, construction activity, construction resource, construction product, etc., are defined explicitly using "isConstructedBy", "hasConMeth", etc. For example, the relation "isConstructedBy" indicates that a construction product is constructed by at least one construction activity. "isDirectlyAfter" is one of the sub-object properties indicating the temporal relationship between two activities.

The monitoring object sub-ontologies provide semantic and also serve as bridges between the BIM application model and the construction risk knowledge. In BIM models, the objects are represented in IFC standard data schema. However, as Wang and Boukamp (2011) and Pauwels et al. (2009) pointed out, since the semantic issue is not the main aim of IFC, for maximising the capability of representing concepts, IFC relationships usually are too general to represent/indicate more specific semantic. In fact, these domain-specific semantic relationships are very useful for construction risk knowledge inferring and retrieval, as different construction objects, methods have different risks, different risk knowledge needs to be considered. Therefore, the domain-specific semantic will have to be modelled in the corresponding risk monitoring object sub-ontologies. For example, in the building product sub-ontology of deep pit foundation engineering, supportive system walls can be classified into: *Pile_wall, Sheet_pile_wall, Soil_nailing_wall, Soldier_pile_with_wooden_lagging_wall, Underground-Diaphragm-Wall*, etc. In addition to the hierarchy relationship, some logical relationships such as disjoint and equivalent relationships are defined in the ontology.

The relevant information (about the product, activity, resource, etc.) is extracted from the project BIM model and mapped into the concepts defined in the risk monitoring object sub-ontologies. For example, the "beam", used as the brace system during the deep pit foundation excavation engineering in a BIM project model, should be mapped into ontology concept "strut". In this way, the semantics of the extracted information are represented explicitly, and can be used to describe the retrieval requirements of risk knowledge. This is very useful for risk knowledge retrieval, since "strut" has its own specific risks during construction.

As well, the risk monitoring objects are used as a bridge to dynamically link the risk knowledge with the BIM application model. According to the dynamic nature of construction project and the context-sensitivity of risk management, the risk knowledge base should be queried according to the project situation to recommend/retrieve the proper risk knowledge, since a project has its own specific constituents and environment which constitutes the risk context. In other word, the risk knowledge should be dynamically linked to the project models.

The ontology-based semantic inferring and retrieval enable the dynamic link mechanism between the applicable risk knowledge and the risk monitoring objects. Once the specific risk monitoring objects are used in the BIM application model, the risks related to this monitoring object will be retrieved from the risk knowledge base. For example, the construction equipment Crane usually has the potential risk–load falling. Therefore, if the crane is used in a construction process, then the risk "lockset fracture" can be inferred and be linked with the construction model in which cranes are used as the construction equipment. Obviously, the dynamic link mechanism helps deal with the dilemma mentioned above, to some extent. In this way, the risk knowledge does not have to be directly statically linked to the construction project model. This will bring some potential benefits. For example, if a construction project model is replaced by other application models involved risk decision, the risk knowledge can be still reused. This improves the risk knowledge reuse and the generality and flexibility of our approach.

4. A prototype system based on the framework

In construction design domain, the Prevention through Design (PtD) is a methodology for proactive risk identification and control, which has been proven safer and more cost-effective than reactive hazard management (Gangolells et al., 2010; Gambatese, 2008). Kamardeen (2010) proposed the thought of integrating PtD knowledge base with BIM models for BIM-based Prevention through Design. Likewise, since different selections of the construction methods and construction processes mean that different risk monitoring objects and their possible risks need to be monitored, the ability to identify risks as early as possible and implement adequate controls is important during the construction stage. However, it is unlikely for engineers to possess all knowledge and experiences required for identifying every potential risk in the broad scope of work.

Given above background, based on the framework and methodology given above, a prototype system is developed as a tool to facilitate the construction risk knowledge management and reuse in hope of improving the construction risk analysis process indirectly. In term of functions, the system aims to: (1) aid users in identifying the construction processes and the potential risks of monitoring objects; (2) aid users in analysing the risk factors and risk paths; and (3) aid users in taking risk/event precautions to prevent the occurrence of an accident due to an identified risk. In term of features, the system (1) enables the semantic validation and search of risk knowledge and risk monitoring objects and (2) the risk knowledge and project models are integrated in a dynamic and flexible way.

In the system, the interdependence between risks, risk factors and risk paths is modelled into a semantic knowledge network, which provides a visual risk knowledge map. Meanwhile, the construction risk knowledge is decoupled from the BIM project model, by the semantic inference and retrieval mechanism. Thereby, the construction risk knowledge does not have to be linked to the objects in BIM project model explicitly.

4.1. Prototype system structure

The prototype system is developed on Microsoft's .NET Platform. It is comprised of a construction risk knowledge base, a BIM project model management module and a knowledge retrieval and browser module. Fig. 2 shows the process diagram of the prototype system.

The prototype ontology is developed with Protégé and represented in OWL. The semantic reasoning is based on the Pellet reasoning engine which is called by Protégé API. The commercial BIM tool Revit is selected to create the 3D BIM project model, NavisWorks is used to scan the model. The retrieval module is developed in the java platform—Eclipse in order to call the semantic inferring and retrieval functions of Protégé platform.

The users can view the 3D BIM, and once users select a construction component via the mouse click, the system calls the Navisworks.NET API to extract information from the selected components, and sends this information to the knowledge retrieval module. Then, the knowledge retrieval module calls the Protégé OWL API to perform the semantic retrieval functions. Finally, the retrieved knowledge is displayed.

4.2. Ontology and construction risk knowledge base

In the prototype system, the typical construction risk knowledge in the deep foundation pit excavation engineering is collected according to the risk ontology model, including the contiguous bored pile retaining wall, underground diaphragm wall, etc. The construction risk knowledge is developed in the Protégé platform, as shown in Fig. 3, and stored as the instances of this ontology model. The Protégé platform provides an environment for creating, editing and saving the OWL ontology in a visual way. Pellet v.1.5.2, is selected as the reasoning engine to provide standard inference services.

As Dikmen et al. (2007) pointed out, causality relationships among risks and risk factors lead to a network structure of risk paths. Compared with the risk checklist, the "cause-and-effect" relationships among the risks and their risk factors form "a network structure, rather than a one-way hierarchical structure". Here, the risk path is extracted using the method developed by Zhong and Li (2014), in which Fault Tree Analysis is used as the risk path extraction tool. Only the topological structure, the upper-level, and the lower-level elements are linked using the object

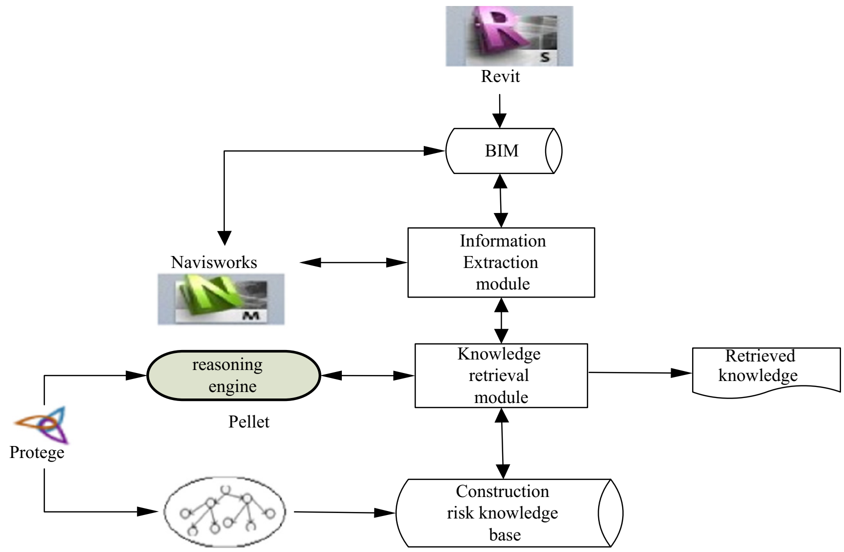

Fig. 2. Structure of the prototype system.

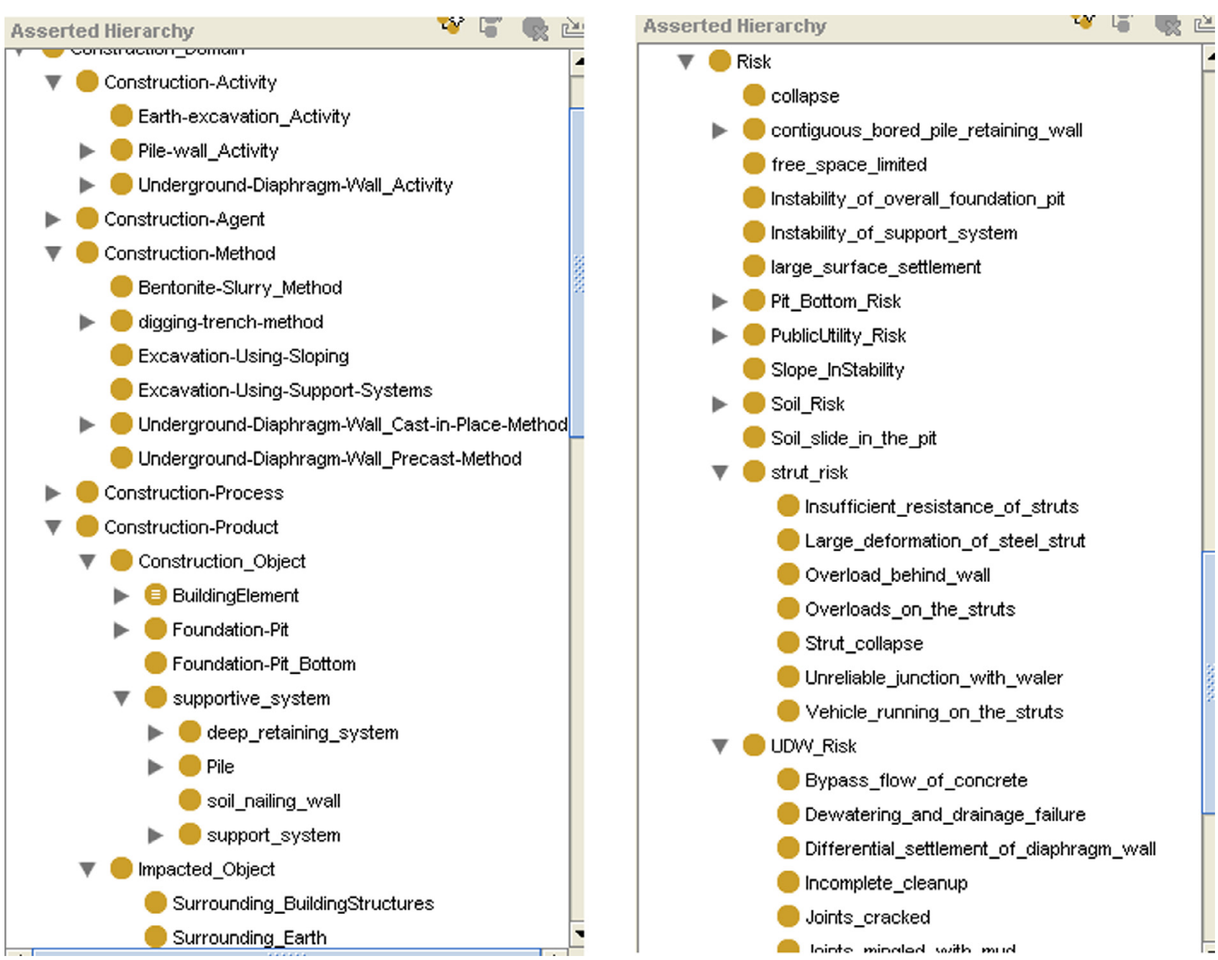

Fig. 3. Fragment of the ontology knowledge in Protégé-OWL 3.4.6 screenshot.

property "Cause", and the logic relationships between these elements can be modelled with risk reasoning rules.

For example, the risk events associated with steel struts during the deep foundation pit excavation are transformed, from a FTA diagram given by Zhou and Zhang (2011), into a small section of the Resource Description Framework (RDF) of the construction risk path knowledge, as shown in Fig. 4. A RDF model is a collection of triples, each consisting of a subject, a predicate, and an object. The risk factors and their causality relationships are modelled into risk paths by the semantic relationships "Cause".

Top event	Middle event	Basic event
Strut collapse	Overloads on steel struts	Vehicle running on the struts
		Machine crashes
		Overload behind wall
	Insufficient resistance of steel struts	Unreliable junction with water
		Effects of adjacent building loads
		Unsuitable design parameters

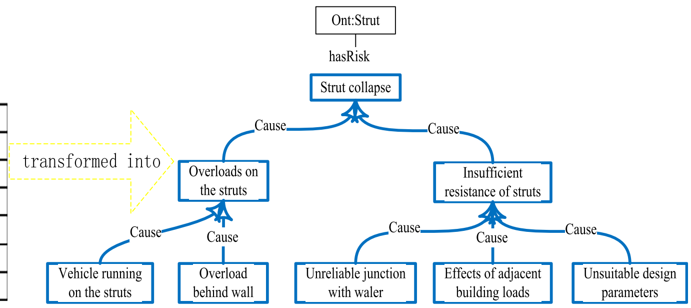

Fig. 4. Risk and its direct and indirect risk factors.

All risk paths with their risk monitoring objects form a risk knowledge semantic network, in which the construction elements, together with the related risks and their risk factors are interweaved. This risk network provides a visual risk knowledge map, from which, the interactions and interdependences between risks, risk paths can be captured. This risk knowledge semantic network can be used as a risk knowledge base. Not only explicit knowledge is included in this knowledge base, but also implicit knowledge can be inferred based on the defined rules. Based on the semantic representation, the risk knowledge can be interpreted and reused by machines. It offers the capability of semantic inferring and semantic search, which helps to improve the efficiency of knowledge reuse.

In order to illustrate visually, also for the simplicity, a small part of the RDF of a simplified construction process linked with the potential risks is shown in Fig. 5.

Web Ontology Language (OWL) is selected to encode the construction risk knowledge. OWL enables all this information to be linked together and represented semantically in one semantic network. The risk knowledge defined in Protégé is exported into ". OWL" file, and stored in the risk knowledge base. The OWL file can be managed by the ontology management tool. The information in a semantic web can be easily processed using techniques driven by logic, including the appropriate standard query languages and rule languages.

4.3. Project information extraction

In the prototype system, the typical construction components, such as foundations, floor slabs, various piles (high-pressure rotary jet grouting pile, concrete mixing pile, etc.), steel struts, and walls, in the deep pit foundation engineering of the Wuhan International Finance Centre project, are modelled.

In this prototype system, the information about component type, resource, construction activity of building elements is added into the project model via project parameters. In BIM, there is no standard format (Shen and Chua, 2011) to input/output for non-geometry data. The different project model creators may represent the same information differently. In this research, these parameters are described using concepts from the corresponding risk monitoring object sub-ontologies. In this way, the information extracted from the project model can be directly put into the retrieval module, without the need of mapping the extracted information into the concepts of the corresponding risk monitoring object sub-ontologies, since the semantics can be inferred in the ontology.

4.4. Construction risk knowledge reasoning

Traditional retrieval technology is based on keywords and uses simple keyword matching rules. Such a model misses the actual semantic information of the text, therefore, only retrieval words in the retrieval objects may be retrieved, and similar semantic concepts to the query request cannot be retrieved due to using different words, which greatly reduces knowledge sharing.

In the retrieval module, the retrieval is based on the ontology and semantic web technology. The matching engine plays as the hub to link semantics in the OWL file with the risk knowledge and the query condition information extracted from BIM project model.

The match algorithm is based on the taxonomical reasoning and rule reasoning. Taxonomical reasoning is based on the taxonomy structure of concepts in the ontology. In the taxonomy structure of an ontology, "Upper and Lower" relationship defines upper and lower relation among concepts. For example, in the product sub-ontology for the deep pit foundation engineering, brace system walls can be classified into: *Pile_wall, Sheet_pile_wall, Soil_nailing_wall, Soldier_pile_with_wooden_lagging_wall*, and *Underground-Diaphragm-Wall.*

When retrieving a concept, its epigynous and hypogynous concepts also can join in the query conditions. In this way, the taxonomy reasoning can be used to expand the search via the semantic extension (including synonymous, upper and lower expansion, etc.)

Rule reasoning is based on axioms in the ontology. Axioms are used to regulate and constrain the behaviours of concepts in the taxonomy and the relationships linking concepts.

In the rule reasoning, Semantic Web Rule Language (SWRL) is used to represent rules. A SWRL rule contains an antecedent part and a consequent part. Once the antecedents of a rule are satisfied, the rule is triggered to execute risk inferring. After executing the rule, the new facts are deduced. Then, the other rules, whose antecedents are satisfied basing the new facts, are fired sequentially. Since the SWRL rule is expressed in terms of ontology concepts (classes, properties, individuals) and the construction context under which the risk or risk event may happen is modelled with ontology concepts as well, the context-driven risk identification can be implemented.

There are two kinds of SWRL rules: the risk inference rule and risk query rule. SWRL rules are not hard encoded in the system, but are stored in a separate knowledge base (as shown in Fig. 6) which is associated with the ontology used in the system. The SWRL rules can be updated whenever needed.

For example, this rule can be used to infer that the Underground-diaphragm-wall may have the risk "*LeakageofDiaphragmWall*", when "*JointMingledwithMud*" and "*JointCrack*" coexist.

Underground-diaphragm-wall(?udw) ∧ isPartOf(?joint,?udw) ∧ Joint(?joint) ∧ hasRisk(?joint,?jmmRisk) ∧ JointMingledwithMud (?jmmRisk) ∧ hasRisk(?joint,?jcRisk) ∧ JointCrack(?jcRisk) ∧ Leakageof DiaphragmWall (?ldwRisk) → hasRisk (?udw,?ldwRisk)

Using SWRL and appropriate reasoning approach, the ontology can help infer new information and knowledge for better query conditions and more complete description of risk knowledge contents.

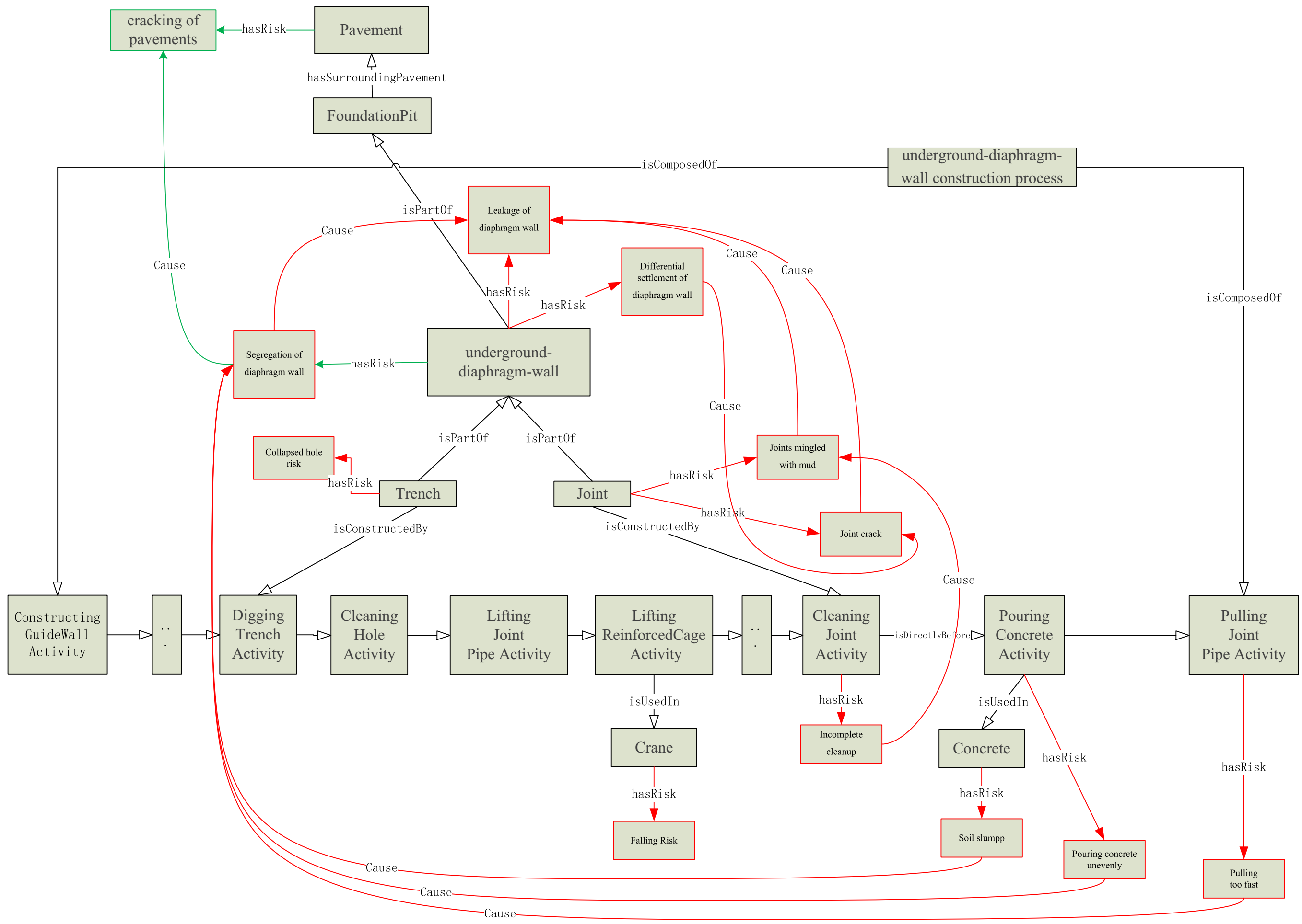

Fig. 5. Fragment in RDF of the construction risk knowledge for the Underground-diaphragm-wall system.

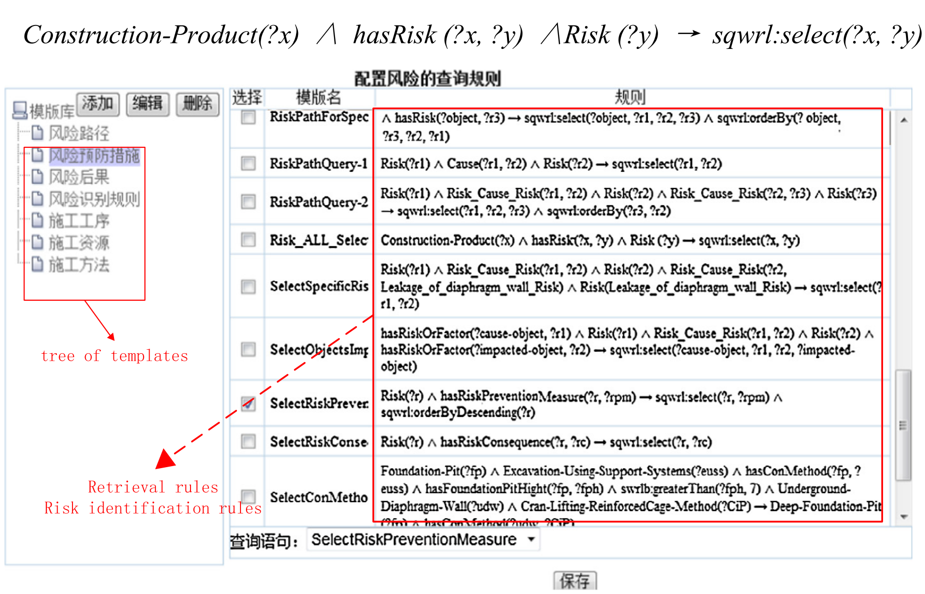

Fig. 6. Interface of the knowledge base.

The risk retrieval rules are used to find the applicable risk knowledge.

In the rule base, some general rules are predefined about construction process, resources, potential risk and their risk factors, risk prevention precautions. For example, one of retrieval rules for the potential risks of risk monitoring objects is defined as follows:

Construction-Product(*?x*) ∧ *hasRisk* (*?x*, *?y*) ∧ *Risk* (*?y*) → *sqwrl:select*(*?x*, *?y*)

The retrieval module enables users to compile the query condition information from BIM into SWRL/SQWRL, and to execute the reasoning and retrieval function.

The retrieval configuration interface is set in the knowledge retrieval module to enable users to define what kinds of knowledge will be retrieved and displayed. For example, users may only choose to retrieve the risks and their risk paths with given risk path depth. As shown in Fig. 6, the retrieval configuration interface support us to manage (add, edit and delete) risk knowledge and rules. This knowledge is organised in the category tree, including the risk identification, risk path, risk consequence, risk prevention measure, construction process and method, etc.

Once the retrieval configuration is done, the retrieval module filters the risk rule base to select specific rules. As shown in Fig. 7a, the configuration interface setting indicates that the risk path with depth 2 will be retrieved and shown.

5. Prototype system application and discussion

5.1. A case application

The case application is to illustrate the prototype application on a real life project. Considering that the feedback of the case study is limited to a specific project, furtherly in a more wide range, we use a questionnaire survey to acquire the opinions from the construction risk and safety management practitioners about the potential benefits.

The prototype system is applied in the construction risk analysis of the deep foundation pit excavation of Wuhan International Finance Centre project. The reason why this project was chosen was that this project utilised BIM tools for the purpose of construction plan compliance checking (Luo and Gong, 2015), in which the BIM model is available and many construction components are modelled into it. The deep foundation pit is a rectangle with the length of 304 m and width of 121 m. The underground diaphragm walls and cantilevered piles are used as the foundation excavation brace system. The underground diaphragm is also taken as the outer wall of the basement structure, and the steel upright and cast-in-place concrete piles are used as the vertical brace system. The system is used by the safety management department of the general contractor of this project, as a knowledge tool to support the construction risk analysis process (including the potential risk identification, risk prevention plan making). That is to say, this system is used to assist the risk identification process, other than to directly identify the construction risk, taking advantage of computer-aided approaches that replace or assist in traditional management practices.

The main problems faced by the safety management department of the general contractor can be summarised as follow:

(1) Construction risk knowledge are scattered and fragmented across regulations, accident records, best practices and experts' experiences. It is time-consuming for them to find and reuse the relevant knowledge.
(2) In the real practice, the potential construction risks identification and the risk prevention planning is error-prone, due to the limited time, the unfamiliarity with the relevant regulation and lack of experience, etc.
(3) It is difficult for the engineers to share the risk knowledge, since the risk knowledge is represented in paper or electric documents.

So, computer-aided construction risk analysis and prevention plan approaches have the potential to assist in the management practices. In this case application, we try to use the prototype system to take more full use of the risk knowledge in BIM environment, via providing knowledge needed for the process of the risk analysis task. Here, we need note that, the system does not automatically implement the risk identification and prevention plan definition.

Not long before this case application, the safety management department just finished the construction plan risk review meeting on the deep foundation pit excavation, in which the two-dimensional construction drawings were given and the experienced engineers listed the potential risks using the experience in their own brains. However, this process is time consuming and error-prone.

The participants of this case application include four safety engineers (two senior engineers with eight years of experience and two young engineers less than four years of work experience)

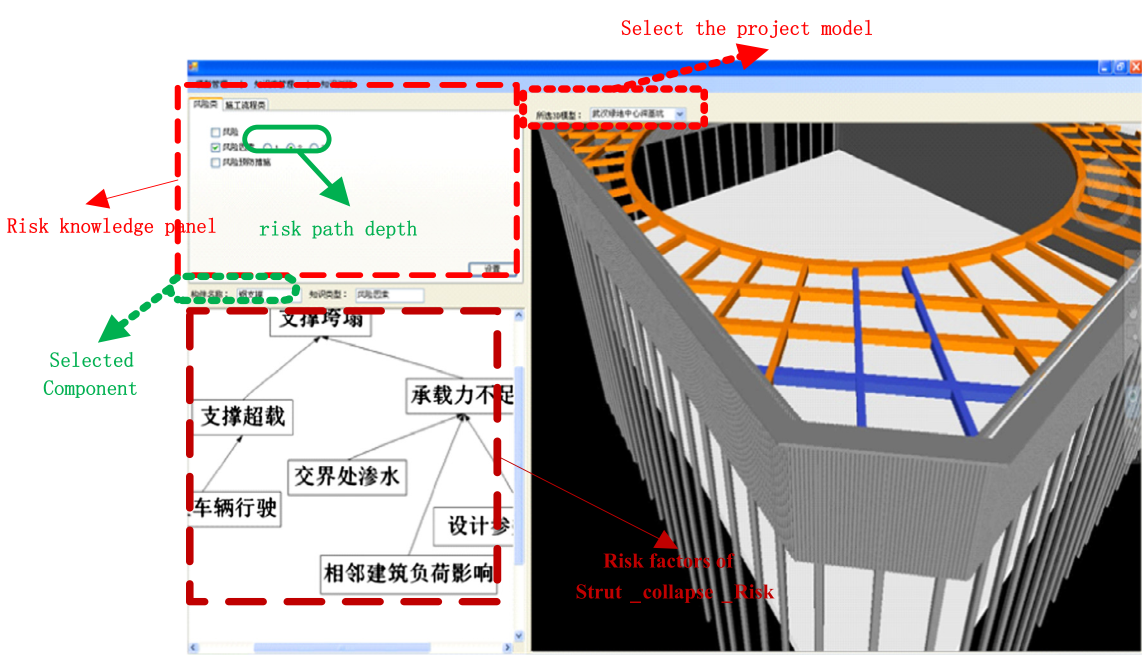

Fig. 7a. Screenshot of the risk path retrieval.

and one manager, who are familiar with the construction safety and risk problems. They use this prototype system to help themselves find the potential construction risk check list of the construction object and their risk prevention plans.

Technically, once the engineers (users) input the construction information into the system, the related potential risk or risk path and their risk prevention measures can be recommended. Based on the system, the construction plan risk analysis can be taken as the process of risk knowledge retrieval.

The application process follows next steps:

(1) Get BIM project models and the relevant information added into the system.
(2) Get construction risk knowledge prepared and formalised into owl and SWRL rules.
(3) Use the risk knowledge inference and retrieval functions to get the potential risks and their risk prevention measures.

In this case application, we limited the scope in those components related to the deep pit foundation excavation during the construction plan risk analysis.

Before using the prototype system, the stratum information of the location, the underground water, surrounding building/structure, the municipal works (e.g., gas tubes, water pipes, and waste pipes), etc., was prepared in the BIM model, since construction risk management covers diverse kinds of information, e.g. the building elements. Information delivery manual (IDM) and model view definition (MVD) are effective tools to define the information needed in BIM model for given certain stage or application purpose. In this case project, there are only two-dimension design drawings, therefore the information was collected manually and typed into BIM. Some information was collected from the design stages of architecture and structure, some information was collected from the deep foundation design. The collected information finally was put into the BIM model.

The risk inference and retrieval rules are crucial to the successful application of the prototype system. In this case application, the typical monitoring objects were modelled into BIM, and the risk knowledge was collected and formalised into the ontology model and risk rule base.

In the prototype system, some general risk rules had been predefined in the knowledge base. In this case application, some specific risk rules need to be defined. For example, once a specific construction object is selected (clicked in BIM), the general risk query rules may be customised with the relevant information extracted from the construction objects in BIM. For instance, when the component "steel strut" is clicked, the template for risk path with depth 2 is instantiated into the retrieval rule for the construction component "steel strut":

Risk(?r1) ∧ Risk_Cause_Risk(?r1, ?r2) ∧ Risk(?r2) ∧ Risk_Cause_Risk(?r2,?r3) ∧ Risk(?r3) → sqwrl:select(?r1,?r2,?r3)

subclass

Risk(?r1) ∧ Risk_Cause_Risk(?r1, ?r2) ∧ Risk(?r2) ∧ Risk_Cause_Risk(?r2, ?r3) ∧ Strut_collapse_Risk(?r3) → sqwrl:select(?r1, ?r2, ?r3)

Where "Strut_collapse_Risk" is a subclass of "Risk" and "Risk_Cause_Risk" is the sub-object property of "Cause".

As shown in Fig. 7a, three functions are listed in the tool bar: project model management, construction knowledge management, knowledge retrieval and browser. In the project model management module, different project BIM models or construction component models can be uploaded and shown. Users can select one of the project models and view it (in the right side) and then pick (by mouse click) one of the components modelled in this project BIM model.

In the knowledge management module, the construction risk knowledge is compiled and rules are managed in the category tree (show in Fig. 6).

In the knowledge retrieval and browser module, we divide construction knowledge into two subcategories: the construction risk subclass and the construction process subclass, which respectively correspond to two panels. In the construction risk panel (as shown at the top-left corner in Fig. 7a), furtherly three options (risk, risk precaution, risk path) are given for users to decide how to display the risk knowledge. As shown in Fig. 7a, the steel strut risk "Strut_collapse_Risk" and its risk path with depth 2 are displayed, which means that the risk, direct risk factors and indirect risk factors are shown. A risk path with depth 1 would only display the risk and its direct risk factors.

As shown in Fig. 7b, the construction risk prevention measures for the steel strut risk "*Large_deformation_of_steel_strut_Risk*" and "*Strut_collapse_Risk*" are displayed.

In the construction process panel, furtherly two options (construction procedure, construction resource) are given for users to choose which type of construction process knowledge will be shown at the bottom-left corner.

As shown in Fig. 7c, the construction process is retrieved from the knowledge base, by clicking the component: *Underground-Diaphragm-Wall.*

Underground-Diaphragm-Wall(*?product*) ∧ *hasConTask*(*?product*, *?task*) ∧ *Construction-Task*(*?task*) ∧ *hasConProc*(*?task*, *?process*) ∧ *Construction-Process*(*?process*) ∧ *isComposedOf*(*?process*, *?activity*) ∧ *Construction-Activity*(*?activity*) → *sqwrl:select*(*?product*, *?activity*)

Then, they were asked to assess if the system can improve their work in the following three aspects (the aims of the prototype system) during the risk identification and prevention planning process.

- aid users in identifying the construction processes and the potential risks of monitoring objects;
- aid users in analysing the risk factors and risk paths;
- aid users in taking risk/event precautions to prevent the occurrence of an accident according to an identified risk.

All the participants agreed that the system was useful in the above three aspects during construction risk analysis and offered them additional support of understanding the complex risk relationships. The system could keep them from missing the possible risk items, which was common in the traditional way, and also enhanced the efficiency of making construction risk prevention plans. The comments include: one important advantage is that, not only the potential risk points but also the risk paths between them can be recommended to them. It was very helpful for them to understand the relationship between risks and make the prevention measures of potential risks. Another important feature of the system was the integration with BIM environment

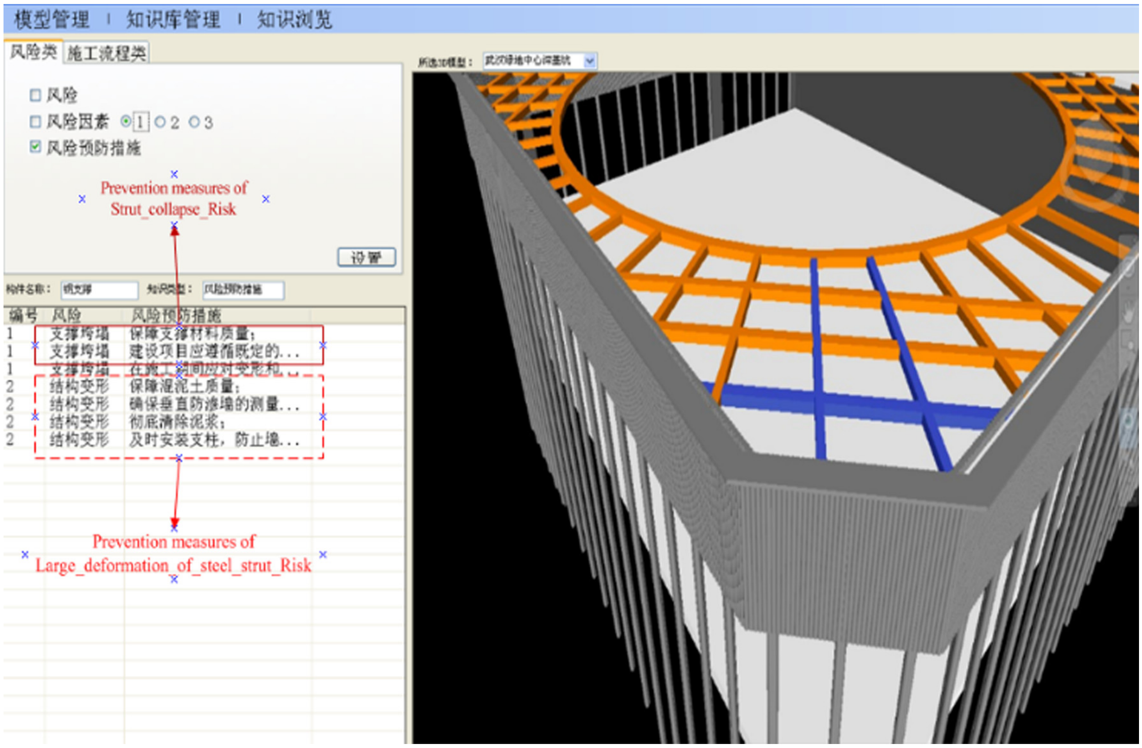

Fig. 7b. Screenshot of risk prevention measures retrieval.

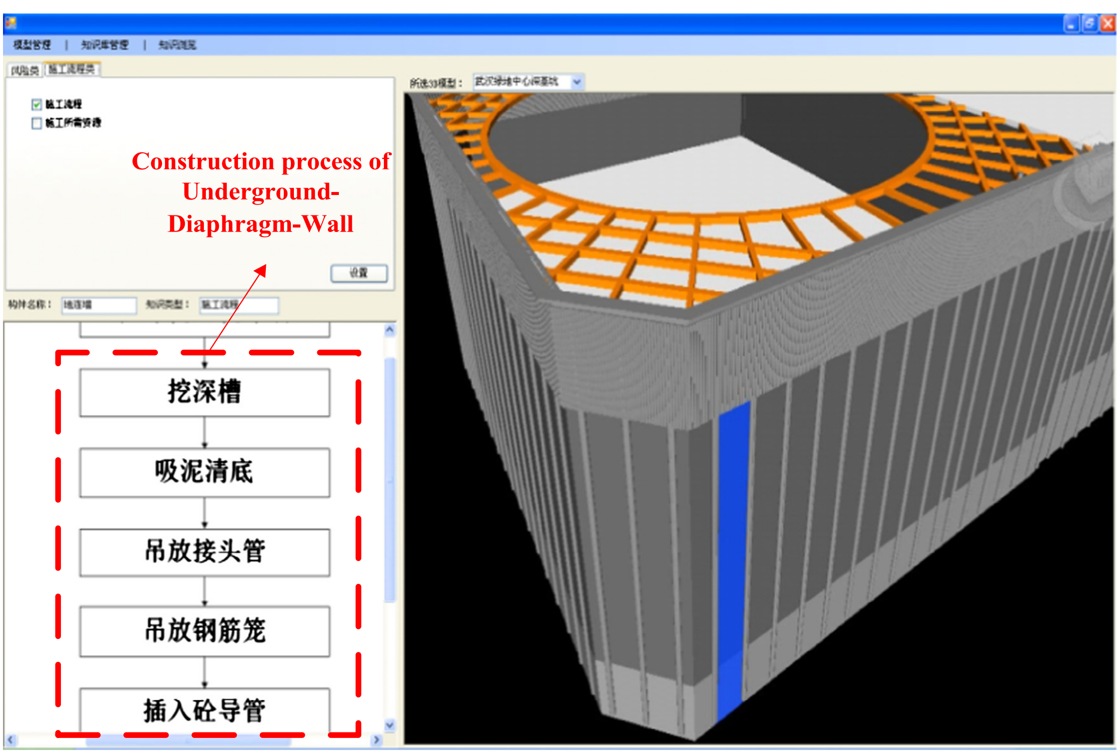

Fig. 7c. Screenshot for the construction process retrieval.

to link the risk knowledge to building elements in BIM visually. Finally, the manager also thought the system was a good training tool for their team members to share or learn construction risk knowledge.

5.2. Potential benefit from the survey

A questionnaire survey was conducted to assess the potential benefits of the prototype system for the construction risk and

Table 1
Result of the survey.

	Investigation item	Very agree (5)	Agree (4)	Neutral (3)	Disagree (2)	Very disagree (1)	Mean score
1	It is necessary and useful to integrate construction risk knowledge and BIM	19%	43%	31%	3%	0%	3.66
2	The system can assist a user in identifying the construction processes and the potential risks of the monitoring objects	21%	60%	19%	0%	0%	4.02
3	The system can assist a user in analysing the risk factors and risk paths	28%	52%	20%	0%	0%	4.08
4	The system can assist a user in taking risk/event precautions to prevent the occurrence of an accident according to the risk path	14%	45%	41%	0%	0%	3.73
5	The system can improve the risk analysis decision-making	24%	63%	13%	0%	0%	4.11
6	The system helps reduce the risk events on construction sites	3%	18%	29%	34%	16%	2.58
7	The system facilitates the learning process and improve the learning performance	38%	56%	6%	0%	0%	4.32

safety management. The main investigation items are shown in Table 1.

The participants include owners, construction safety managers, safety engineer and the field workers, from the department of construction safety in several famous construction contractors, from the construction industry in Wuhan City of Hubei Province. They are selected to evaluate the prototype system because these contractors are interested in construction risk & safety since they are often engaged in large, complex and high risk construction projects. In addition, these contractors have better IT automation level and therefore are more capable of testing the prototype system and providing feedback. During survey, the research team introduced the main functions and features of the prototype system. The participants were then asked to complete the questionnaires and to give their questions and suggestions or issues they were concerned about the prototype system.

The questionnaire includes several items and for each item participants are requested to give their opinions by ranking their degree of agreement. A five level Likert-scale is used in the questionnaire, which is, Strongly agree (SA) = 5, Agree (A) = 4, Neutral (N) = 3, Disagree (DA) = 2 and very disagree (VDA) = 1. The participants were asked to explain any items which they ranked "Disagree" or "Very Disagree". The participants were also asked to give their feedback about the prototype system.

Total 60 copies of questionnaire were distributed, and 58 copies were collected and 55 copies were valid for this research. The results of the investigation were summarised in Table 1.

From Table 1, the overall feedback is on the positive side, and the mean score is all above 3.40, with exception of item 6.

We also recognised that the vagueness of these ranks and the possible difficulty to distinguish the difference among these ranks. However, from the results of the table, for each item, except "item 6", the total proportion of the rank "Very Agree" and "Agree" is greater than "50%", therefore, this can still verify the potential benefits. All the participants think that the proposed system would help in decision making for construction risk identification and risk prevention planning. The survey shows that the prototype system can indirectly improve the risk or safety management performance, via facilitating risk management consideration during construction process planning. Many participants think that many risk events are caused mainly by unsafe working practices of field workers. Even though the system may inform them what risks may occur and how to prevent the risk events, it may be difficult for the field workers to change their working style (way) and unsafe working practices. Nonetheless, they believe the proposed approach would help improve safety on construction sites indirectly. This opinion of the participants coincides with the investigation results by Tam et al. (2004), in which "lack of training", "reckless operations" and "poor safety awareness" are identified as the main factors affecting construction safety.

It is found that almost all participants are very concerned one particular issue which is the availability and feasibility of the system on construction sites, as they are used to the paper-based risk checklist tool. This issue could be resolved via a tablet version of the system. At the same time, many participants also suggest that videos and pictures about the risks and safety accidents should be added to the prototype system. These visual learning aids would make a more direct and real impact on the learners about the risks and their consequences and improve the risk and safety awareness. This suggestion will be added to the future development of the prototype system.

5.3. Discussion

In the prototype system, users can select any 3D components in a BIM environment, and the related construction risk knowledge and documents can be viewed. BIM models provide visual knowledge reuse environment, however, it may be difficult to be implemented successfully if the BIM models are not available. Currently, one limitation of the prototype is the deep reliance on the information describing the construction monitoring objects, provided by BIM project model, such as the construction method and activity. If the information in BIM is incomplete or inaccurate, the construction risk knowledge recommended by the system may be affected. However, in practice many engineers are not familiar with BIM model and rule base development. Therefore, the knowledge experts need take part in the BIM model and knowledge modelling.

Another limitation is the complexity of the semantic representation of risk knowledge, which makes it difficult to maintain. The semantic annotation of the construction risk documents can be introduced to solve this problem. In this case, the accurateness and correctness of the semantic annotation in the documents may greatly affect the knowledge acquisition. As pointed out before, it is very crucial for the risk analysis to have rich risk knowledge. The knowledge experts and domain construction expert need cooperate closely. The knowledge audition is needed to ensure the accuracy and richness of the risk rules.

The practical application of this prototype system is depending on the richness of the construction risk knowledge stored in the system. At present, the prototype only contains the typical construction technical risk knowledge for the deep foundation pit excavation engineering. In the future, the construction risk knowledge base in the prototype system should be extended. Meanwhile, it should be noted that, the application evaluation is done only in the given case scenario, and more application cases should be implemented. Even though the case application and the survey showed the benefits of the framework and prototype system, it is acknowledged that comprehensive testing and extensive application to a wider construction risk monitoring objects and projects will be needed to further help validate both the model and the framework. Moreover, this paper mainly focuses on the risk related to construction activities and other types of risk are not considered, such as the material delivery risk. Therefore, other types of risk still need to be included in the future.

The proposed methodology is based on the ontology and semantic web technology. The predefined prototype ontologies are used to handle semantics. Ontology modelling and semantic representation of the construction risk relevant knowledge is herculean and time-consuming. At the same time, in our methodology, the compatibility of the ontology with the existing BIM standard IFC and some popular classification standard, e.g. OmniClass™, UniFormat™, is not covered and is worth the further study.

6. Conclusion

Construction risk identification and safety management are knowledge-intensive. In this paper, an ontology-based methodology for construction risk knowledge management in BIM environment is proposed, and the related risk knowledge is organised semantically and dynamically linked with the specific building objects in a BIM environment. The methodology facilitates the knowledge reuse during the construction risk analysis process for risk knowledge management tool. A prototype system of such tool is then developed and a case application is implemented to demonstrate the risk prevention through construction process/method selection, including the risk factors identification, risk paths reasoning and risk prevention plan recommendation. The construction risk knowledge stored in the knowledge base is retrieved and displayed by selecting the construction components in the BIM model. In term of features, the system (1) enables the semantic validation and search of risk knowledge and risk monitoring objects and (2) the risk knowledge and project models are integrated in a dynamic and flexible way. The potential benefits are investigated through the questionnaire survey. The survey shows that the prototype system can improve the risk or safety management performance from the perspective of the knowledge management and reuse.

Acknowledgements

This research is partly supported by "National Natural Science Foundation of China" (No. 71301059) and "Fundamental Research Funds for the Central Universities" (No. 0118240099).

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