



A study of ontology-based risk management framework of construction projects through project life cycle

H. Ping Tserng^{a,*}, Samuel Y.L. Yin^{a,b}, R.J. Dzung^c, B. Wou^d, M.D. Tsai^e, W.Y. Chen^a

^a Department of Civil Engineering, National Taiwan University, No. 1 Roosevelt Road, Sec. 4, Taipei, Taiwan

^b Ruentex Group, 14F, No. 308, Section 2, Bade Road, Taipei, 104, Taiwan

^c Department of Civil Engineering, National Chiao-Tung University, 1001 Ta-Hsieu Road, Hsinchu, 30050, Taiwan

^d Department of Civil Engineering, National Chiao-Tung University, 1001 Ta-Hsieu Road, Hsinchu, 30050, Taiwan

^e Division of Construction Engineering and Management, Department of Civil Engineering, National Taiwan University, No. 1 Roosevelt Road, Section 4, Taipei, Taiwan

ARTICLE INFO

Article history:

Accepted 13 May 2009

Keywords:

Process-oriented knowledge management

Knowledge flow

Project risk management

Workflow

Engineering decisions

Ontology

ABSTRACT

The process knowledge assets make a substantial contribution to the risk management (RM) for contractors in the construction phase. To effectively reuse these assets, knowledge extraction becomes a significant research area. This paper was designed to explore an approach to conduct knowledge extraction by establishing project risk ontology. Specifically, the study proposed the ontology-based risk management (ORM) framework to enhance the RM performance by improving the RM workflow and knowledge reuse. The ORM framework facilitated the identification, analysis, and response of project risks. This study validated the ORM framework through a case demonstration. Through the implementation and application, the results demonstrated that the ORM framework was able to apply to the RM workflow for contractors, and more importantly, it greatly increased the effectiveness of project RM.

© 2009 Elsevier B.V. All rights reserved.

1. Introduction

The characteristics of the construction industry include product uniqueness, on-site production, and ad hoc project teams with high turnover rate [34,52]. Subsequently, it has been difficult for the construction industry to coordinate, store, and reuse knowledge that is obtained between the organization and its individuals. Therefore, the construction industry needs to acquire, store and reuse knowledge in order to increase project performance. Previous studies had suggested the organization should conduct knowledge management through methods of project reports or lessons learned [15,29,42].

In addition to the aforementioned approach, Process-Oriented Knowledge Management (POKM) emphasizes that, through the combination of knowledge management and workflow process, the organization could increase project performance and purposely accumulate knowledge for future usage [40,24]. Recently, construction studies have explored knowledge management from the process-oriented perspective and studied the effectiveness of the POKM application in: safety management [5,12], design management [4,30], and facility management [44]. The results revealed that these studies primarily applied information technology (IT) tools to integrate the

workflow and knowledge management. Knowledge management was mainly conducted to capture explicit and tacit knowledge related to the workflow to help the user acquire and reuse knowledge with the standard operation procedure within the workflow.

In a previous research paper by the writers [54], the case study verified the POKM model could apply to the contractor's risk management (RM) workflow and therefore enhance the RM performance. Simultaneously, the project risk knowledge base could be built. Following the building of the knowledge base, an inquiry into how to extract and reuse the knowledge base effectively emerged as another important research issue. This study proposed ontology as the solution to investigate this issue. More importantly, the study would concentrate in the project risk knowledge base to study and verify the knowledge extraction model effectively. The study proposed an approach combining expert interview and information retrieval (IR) algorithms to extract the knowledge and develop the project risk ontology. Subsequently, the ontology-based risk management (ORM) framework is developed.

Based on literature review, the construction industry's project environment was usually exposed to a higher degree of risk and faced a significant amount of uncertainties [2,7]. Under such conditions, those decisions made by engineers and project managers were generally under uncertainty [3]. Consequently, project performance for the construction project was subject to risk factors and most projects failed to deal with the risk [18,22]. In particular, during the construction phase of project life cycle, the contractor not only faced risks produced from limited experiences in construction and project execution itself,

* Corresponding author. Tel.: +886 2 23644154; fax: +886 2 23661640.

E-mail addresses: hptserng@ntu.edu.tw (H.P. Tserng), Samuel@mail.ruentex.com.tw (S.Y.L. Yin), rjdzeng@mail.nctu.edu.tw (R.J. Dzung), wubin@cpami.gov.tw (B. Wou), d93521006@ntu.edu.tw (M.D. Tsai), R94521711@ntu.edu.tw (W.Y. Chen).

but was also burdened with risks incurred from the owner or design company [19]. RM, consequently, played a significant role for the contractor. The risk manager is required to possess knowledge in order to conduct risk management [18,26,33,16]. An important concern regarding RM performance is how to reuse the knowledge base effectively. Accordingly, the ORM framework aims to enhance the RM performance through knowledge extraction and reuse.

In this study, the proposed ORM approach was found helpful for the selected contractor when conducting the project risk management. For the project manager (PM), this approach could be of assistance in risk identification, analysis and response. In addition to increasing RM effectiveness, the study verified that the project risk ontology could be developed through acquiring tacit knowledge and extracting explicit knowledge from the organization. To summarize, in this study the ORM approach could support the contractor by increasing effectiveness of RM workflow on the basis of implementing knowledge management.

2. Literature review

2.1. Knowledge management research

Peter F. Drucker [31], the late master of management science, attempted to clarify that knowledge had become the key asset to an organization in modern society. Later, the report from the Organization for Economic Co-operation and Development (OECD) [28] – knowledge, as embodied in human beings (as ‘human capital’) and in technology, had always been central to economic development – more specifically indicated knowledge was essential to Knowledge-based Economy. Therefore, knowledge asset had become a crucial factor for organizational competitiveness [5,15], and was regarded as highly important [29].

The crucial component of knowledge management (KM) is managing knowledge flow that the organization needed [39,17]. Through the application of the KM technique and IT tool, the procedures of knowledge processing could be strengthened to help knowledge flow support the workflow operation in the organization [15,25]. Conversely, Process-Oriented Knowledge Management (POKM) was conducted using the analysis of workflow activities and knowledge requirements, to integrate the appropriate knowledge management with the workflow. Thus, the POKM approach could facilitate the knowledge flow in each organization workflow and improve working performance because of knowledge reuse [40,24,48].

For KM, knowledge processing procedures could be categorized into five steps: knowledge capturing, knowledge editing & validating, knowledge storing, knowledge sharing, and knowledge creating [53,42]. However, knowledge management not only refers to knowledge-based management only, but it also covered the management of knowledge-creating processes, the management of person-to-person knowledge exchange within the organization [49,17]. With reference to Carrillo and Chinowsky's classification [29], the two KM types could be divided into 1) the information technology centric (IT), and 2) the human resource centric (HRM). The HRM and IT types of KM can be regarded as two management models that correlate with tacit and explicit knowledge. For example, explicit knowledge correlates with the knowledge extraction of the enormous and complex project database, i.e., IT type. This presented a research issue about how to reuse the knowledge effectively. To address this concern, previous researchers proposed several verified model to extract the construction knowledge [10], [11], [51]. Thus, these studies foreground the importance of knowledge extraction to the effective reuse of the knowledge.

The available reused knowledge usually encompasses explicit and tacit knowledge [15]. The tacit knowledge captured becomes a problem of knowledge reuse [20,47]. To solve such a problem, many studies suggested that explicit and tacit knowledge management should be conducted by combining the POKM approach and IT system

development during the workflow [5,12,44]. This solution adopted the systematic process support to retrieve information and knowledge, and to record the users' decisions and tacit knowledge effectively during the working process. In summary, these studies have proposed the verified models to support the capturing of the tacit knowledge by embedding the KM mechanism into the workflow.

2.2. Information retrieval and ontology application in construction industry

Information retrieval can be defined as a technology relating to the representation, storage, and organization of, and access to information items. [8]. To simplify it, the goal of IR in the technical aspect is to assist the users in quickly locating relevant and critical knowledge with much more ease. As the construction industry is characterized by its enormous, complex project data, how effective the knowledge dissemination and information sharing functions within the organization are can provide high level value for the organization [4]. This field of technology is, therefore, recognized as an important aspect in the construction industry applications.

Ontology is a formal, explicit specification of a shared conceptualization [46]. Specifically, ontology could be referred to the explicit formal specification of the concepts in a specific domain and the relations among them. Therefore, the two main elements of ontology are concepts and relations. Ontology could be relevant in the research field of artificial intelligence, representation of knowledge, semantic web, system integration and problem solving techniques [1]. In the construction management academia, ontology had been applied to knowledge representation, decision making, and information integration [1,52,23,43].

The development of ontology requires a great deal of time, cost, and expertise [23]. Previous efforts have focused only on a specific topic [36,37,44,1]. Conversely, the most notable industry-wide efforts that have been validated include the Industry Foundation Class (IFC) and the e-Cognos project [36,37,52]. Most of the validated ontology application models, however, have focused on a specific domain.

In previous studies, Kosovac et al. [6] assisted engineers with IR by constructing a thesaurus. Lin and Soibelman [23] utilized a specific ontology along with the algorithms for query expansion to enable users to retrieve and rank the information effectively. Moreover, semantic algorithms of the IR model were applied in the development of several verifiable knowledge management systems (KMS) to support architecture design and the organization of project documents [30,9]. In 2006, Rezgui [52] presented an application that combined the semantic algorithms and the construction industry ontology to construct the automatic knowledge-feeding system based on the result of knowledge extraction. In summary, the previous studies proposed several successful models which verified that IR algorithms could support, retrieve and reuse of knowledge. Furthermore, the IR algorithms could be applied with ontology.

2.3. Construction risk management

Tah and Carr's studies [18] indicated that RM procedure was widely accepted as the chief role to affect RM. A good procedure design enabled a systematic and consistent approach to implement RM; hence, many studies were dedicated to research the RM procedure [7,18,27]. Moreover, since risk management was important to project performance, it had also been built into “A guide to the Project Management Body of Knowledge (PMBOK guide)” framework proposed by [32]. Through case studies, it was also proved that the approach and tool mentioned in the PMBOK guide were influential to project performance [22].

Another important RM research objective was to develop risk management approaches through experience and knowledge application. Hence, many studies discussed conducting risk management on knowledge reuse bases [18,35,45,27,16]. In these studies, fuzzy model,

Analytical Hierarchy Process (AHP) and statistical techniques were adopted to transform professional experience and case knowledge into the RM model for achieving knowledge reuse. Based on these quantitative models, these studies found methods to enhance RM effectiveness via knowledge reuse. Furthermore, additional studies were aimed at the specific project objective as the guideline to propose the management model according to RM knowledge [50,11,7,21]. All of these studies confirmed that RM knowledge was essential to RM enhancement and RM is influential to project performance.

The previous RM investigation on construction industry pointed out that the most common RM problem during the project construction phase was the insufficient risk identification which tended to cause the inadequate RM activity during the execution phase [22]. Another investigation concerning the British construction industry indicated that most companies would conduct risk management based on their previous experience, not on formal risk analysis techniques due to time and knowledge insufficiency [2]. Subsequent studies also concluded the same results [26]. These investigation results, also, demonstrated that the typical RM problem consisted of complicated risk analysis techniques resulting in time and training insufficiency leading to failed application of those techniques.

More recently, after construction companies began to adopt RM techniques to analyze risks, the following studies recommended that organizations should use qualitative or quantitative techniques to analyze risk [41]. By analogy, qualitative, rather than quantitative, techniques were widely accepted by the construction industries initially. In later years, when the construction companies became familiar with RM techniques, increasingly quantitative techniques were adopted. Further, Wyk et al. [33] indicated that organizations could identify the most appropriate RM application techniques by combination of qualitative, semi-quantitative, and quantitative techniques. In their study, another RM problem for the construction industry was proposed, as well: the organizations usually employed more risk identification and evaluation than risk response and record. By employing less risk response and record, verification for knowledge reuse would be lacking and difficult to apply to the subsequent projects. Thus, it could be concluded that construction RM shall be conducted based on the organization's requirements by using the formal and systematic RM technique. Furthermore, the RM knowledge database shall be renewed via audits and records to achieve the purpose of knowledge reuse and the enhancement of RM performance.

3. Research scope and methods

This study aimed to develop an ontology-based risk management (ORM) framework for the contractor. This study began with a review of the ontology development research. Based on literature review, the study adopted the following process to develop the project risk ontology and ORM framework, including six steps: definition of scope, review of domain authorities, extraction of important concepts, organization of concepts into hierarchy, definition of the property of concepts, and validation [1,43]. For the validation of the ontology, the competency questions, expert survey and case study are the major validation methods [1,43,44]. Moreover, the study adopted the IR algorithm to develop the dynamic ontology extraction tool to supplement and update the ontology. Important in this study is while developing ontology, explicit and tacit knowledge for the effective reuse of knowledge must be included. Therefore, the study also included a literature review of the methods of explicit knowledge extracting and the tacit knowledge acquiring mechanism from the literature, and hence established the ontology development procedures.

By implementing the POKM model in RM workflow in the former research [54], the selected contractor built the risk knowledge base. To verify the project risk ontology and the ORM framework effectively, the study would concentrate on this risk knowledge base and the same contractor. Those involved in the case study were the risk

experts and senior engineers to provide a better understanding of the risk profile and risk knowledge. In this case study, expert survey and the case study were adopted to verify the project risk ontology. In order to verify this risk ontology, the study conducted expert survey and several expert workshops to discuss and modify the ontology. Subsequently, the feasibility of the ORM framework and the project risk ontology would be verified via 5 actual project demonstrations. Finally, the ORM framework and case study results would also be validated via extensive discussion with domain experts.

4. Development of ORM framework

The development of the ORM framework included four primary domains: (1) the development of project risk ontology; (2) the extraction of the risk knowledge base; (3) the establishment of the ORM approach; and (4) the dynamic ontology extraction tool. Based on the verified model of the ontology development and application in the construction industry, the ontology development process includes six main steps. The research process included six steps as illustrated in Fig. 1. The conceptual model of the proposed framework was shown in Fig. 2. In this model, the project risk ontology played the most vital role of the entire framework. The ORM approach was developed based on the characteristic of project risk ontology and the application problems of RM workflow. The knowledge extraction model encompassed both explicit and tacit knowledge. As previously indicated, the developing of ontology involves much expertise and many case studies. Moreover, the involvement of domain expertise in intensive interviews and the iterative development of procedures are crucial for ontology development [55,38].

4.1. Definition of scope

The ORM framework was established to enhance RM performance through ontology development and application. The RM workflow and demand knowledge analysis are essential to the ontology development process. As the aforementioned studies indicated, knowledge record was influential to the subsequent project during RM workflow, since complete knowledge flow is necessary for the knowledge base.

For the ontology development, activity analysis is elemental to identify the scope. This study performed the activity analysis based on the literature review. As the previous studies showed, that the industry

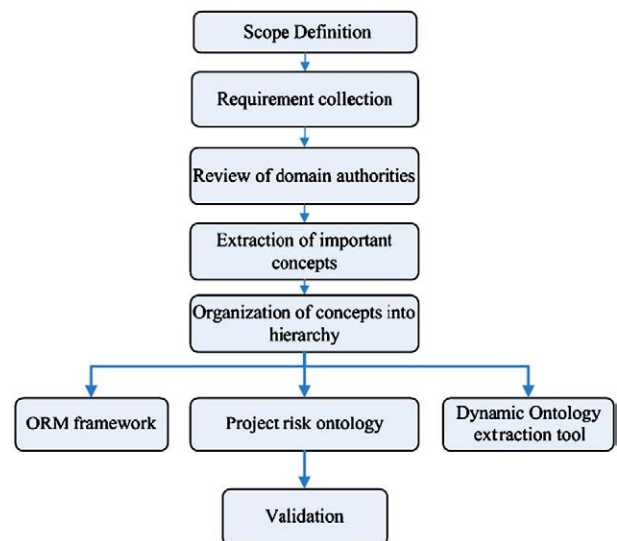


Fig. 1. Study methodology flowchart.

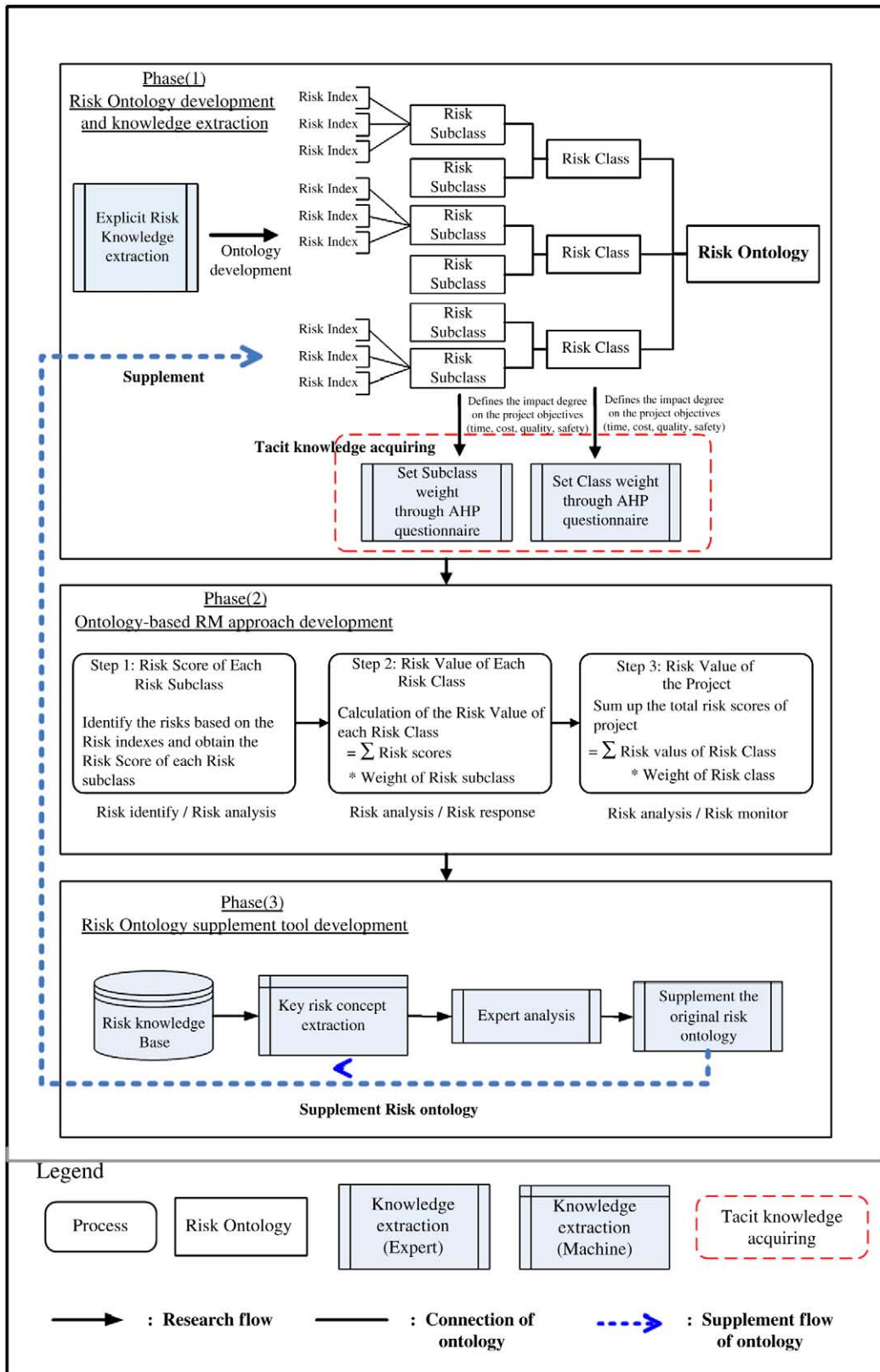


Fig. 2. Conceptual model of the proposed framework.

widely accepted RM as a formal and systematic flow composed of five steps: risk plan, risk identification, risk analysis, risk response, and risk monitor and feedback [18,10,41,33]. Accordingly, this RM workflow was the basis for the developing the ontology to propose a more generalized solution to the construction practitioners.

Analysis of knowledge demand of RM workflow shapes and defines the scope. This study also performed activity and knowledge interaction analysis of RM workflow. According to Tah and Carr's study [18], the standard methodology such as IDEF0 could be used to model the process and information flow of RM workflow. Therefore, this

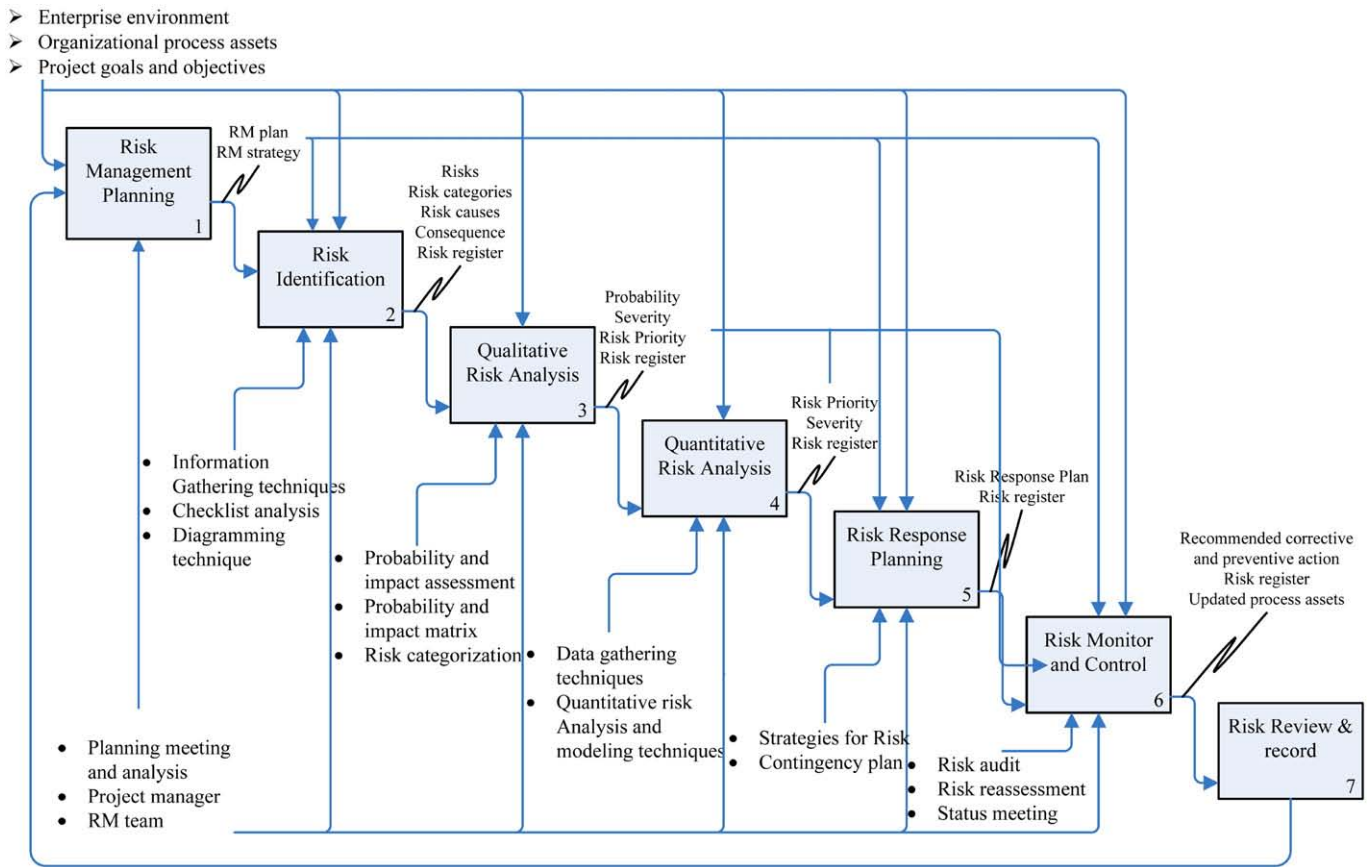


Fig. 3. Activity and knowledge interaction analysis of RM workflow.

study adopted IDEF0 to model the activity and knowledge interaction among the RM workflow as illustrated in Fig. 3. In Fig. 3, each activity box shows the main activity of the RM framework. Moreover, this diagram also showed the knowledge flow and its interaction with RM workflow. In Fig. 3, four arrow classes are illustrated in each activity box: Input arrow, Output Arrow, Control Arrow, and Mechanism Arrow. This study analyzed the demand knowledge flow of each activity and its arrows classes, as illustrated in Table 1. As presented in Table 1, there are 2 main RM knowledge types: (1) explicit knowledge: RM knowledge, including historical risk knowledge, RM template and predefined RM approaches; and (2) tacit knowledge: RM knowledge and experience that resided with individuals. In summary, the analysis of process domain and knowledge domain not only defined the scope, but also identified the knowledge resource of ontology development.

4.2. Requirement collection

Previous studies alluded to the difficulties in applying formal RM procedures. The time consumed and the complexity involved could lead to failed application of RM techniques. Moreover, the application of existing qualitative and quantitative techniques suffered for the insufficient knowledge and effectiveness. Therefore, the ORM framework was proposed to decrease the complexity of RM workflow and increase effectiveness.

To develop the ontology requires combining both explicit and tacit knowledge for reuse. The knowledge in RM workflow needed further analysis. Based on Table 1, this study designed different knowledge gathering means for different RM knowledge types, as illustrated in Table 2. As indicated in Table 2, the main RM knowledge type that can be acquired within the organization is explicit knowledge. Contrarily, the

tacit knowledge (RM experience) which is demanded throughout RM workflow is difficult to capture and reuse. Moreover, the lack of tacit knowledge often presents problems in RM. Therefore, the means designed to capture RM experiences among different scenarios must be of equal vigour in the ontology development. Moreover, for implementing the ORM framework, Table 1 would be applied as the risk knowledge check list and Table 2 serves as risk knowledge capture means.

4.3. Review of domain authorities

The review processes for domain authorities include a review of existing classification systems and ontology. In the risk classification domain, previous researches proposed inclusion of several classification systems. However, most of those systems concentrated on specific RM domains, i.e., BOT project, scheduling, and safety management [7,45,10]. In contrast, the industry wide risk classification domain, the hierarchical risk-breakdown structure (HRBS) developed by [18], would be relevant to this study. Thus, this study adopted the HRBS classification as the underlying ontology. As this study selected a specific domain of ontology development and application, the industry wide ontology such as IFC and e-Cognos were only adopted as the referential source for the project risk ontology development.

The expert workshop is useful for this step to provide the basis of ontology development. In order to propose a more feasible ontology for the following verification, domain experts from the selected contractor were invited to modify the underlying classification. There were 3 expert workshops held with 25 participants to discuss the underlying classification and to evaluate other classifications from the literature review in 2006. And the results provided the basic taxonomies for the following ontology development.

Table 1
Activity and knowledge flow analysis of RM workflow.

RM activity	Arrow type	Description	Demand RM knowledge
Risk management planning	Input arrow	Review/confirm of project related <ul style="list-style-type: none"> • Enterprise environment • Organizational process assets • Project goals and objectives 	<ul style="list-style-type: none"> • Predefined RM approaches • RM experience • Risk categories • RM plan template • RM planning experience
	Mechanism arrow	Based on initial RM knowledge, project manager (PM) and RM team conducts RM planning meeting and analysis.	
Risk identification	Input arrow	Based on the RM plan and strategies, PM reviews and gathers the organizational process assets.	<ul style="list-style-type: none"> • Predefined RM approaches • RM experience • Historical risk knowledge • RM experience • Risk checklist • Risk categories • Historical risk knowledge • RM experience • Historical risk knowledge
	Mechanism arrow	PM uses the appropriate risk identification techniques to identify risks might affect project.	
Qualitative risk analysis	Input arrow	Based on the identified risks and risk profile, PM reviews and gathers related risk knowledge.	<ul style="list-style-type: none"> • RM experience • Historical risk knowledge • RM experience • Historical risk knowledge
	Mechanism arrow	Based on predefined approaches, PM conducts risk assessment.	
Quantitative risk analysis	Input arrow	The probability and impact scale of identified risks.	
	Mechanism arrow	To analyze each risk and its consequence on project objectives.	<ul style="list-style-type: none"> • RM experience • Historical risk knowledge
Risk response planning	Input arrow	<ul style="list-style-type: none"> • Priority of risks and probability of achieving the project objectives • RM plan and strategies. 	
	Mechanism arrow	PM plans and adopts Strategies and responses for uncertainties to reduce threats of risks	<ul style="list-style-type: none"> • RM experience • Historical risk knowledge
Risk monitor and control	Input arrow	<ul style="list-style-type: none"> • Risks profile and its response • RM plan and strategies. • Residual and secondary risks 	<ul style="list-style-type: none"> • RM experience • Historical risk knowledge
	Mechanism arrow	PM tracks the effectiveness of responses. Also, PM identifies and assesses new risk. Last, status meetings are held to review the project risks.	<ul style="list-style-type: none"> • RM experience • Historical risk knowledge • Risk checklist • Risk categories

4.4. Extraction of important concepts

Based on the basic taxonomies, the extraction of important concepts plays the role of collecting the concepts for the ontology development. Previous studies adopted a variety of methods to extract important concepts from the target domain including a review of an existing taxonomy, a review of the literature, an analysis of a sample document, and a conceptualization of IDEF0 [38,43,1]. For implementing the ORM framework, these concept extraction means could also be flexibly adopted for the contractors.

As discussed earlier, the development of ontology required a lot of the expertise. Therefore, in this step, the project risk expert and senior manager interview or workshop were necessary for the major modification of the preliminary set of risk concepts.

4.5. Organization of concepts into hierarchy

Following the completion of the project risk concepts extraction process, the classification framework could be classified into risk knowledge types. In this step, the major class and class hierarchy of the ontological framework could be identified based on the literature

review and case studies [1]. Previous study also suggested that both classification and the balance between depth and coverage [38] could change the development result. However, there is no specific standard for the validation of ontology [36]. Thus, the involvement of domain expertise in intensive interviews and the iterative development of procedures were the most important parts in this step.

In this step, the risk ontology framework composed of risk class, subclass and indexes as shown in Fig. 2 was developed. A risk subclass could also view as risk events. The remaining risk indexes were referred to certain characteristics/instance of risk events.

4.6. Establishment of the ORM approach

As discussed earlier, regarding the collected requirement, the ORM framework aimed to decrease the complexity of RM workflow, increase effectiveness, and develop ontology by combining both explicit and tacit knowledge. The result of activity and knowledge interaction analysis would advance an adequate approach to fulfil these requirements. The qualitative and quantitative risk analysis of RM workflow can provide strong information about project risk. Moreover, previous studies also mentioned that such procedures are

Table 2
RM knowledge and KM means analysis of RM workflow.

RM knowledge	Knowledge type	Description	Knowledge capture means
Predefined RM approaches	Explicit	Predefined RM approaches could be: risk categories, RM templates, risk assess methods, roles and responsibilities.	Documented knowledge acquisition/compilation mechanism
RM experience	Tacit	RM experience could be risk management experience and related experience to certain risk throughout project life cycle.	Interview, project meeting(knowledge community), questionnaire
Risk categories	Explicit	Risk categories are predefined based on the risks historical data through classification.	Construction of knowledge classification/ map
Historical risk knowledge	Explicit	Related project document, risk report, and RM plan.	Documented knowledge acquisition/compilation mechanism
Risk checklist	Explicit	Risk checklist is predefined based on the risks historical data.	Documented knowledge acquisition/compilation mechanism

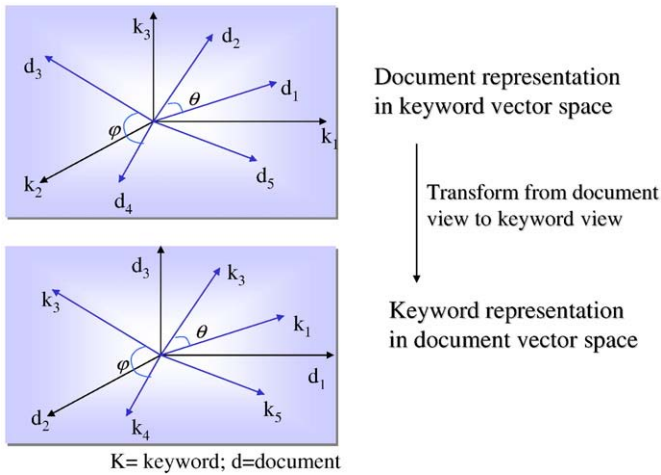


Fig. 4. The keyword view of vector model.

difficult for contractor to apply. Thus, this study would propose the solution to integrate both these procedures.

During the qualitative risk analysis process, the risk matrix calculation helped the risk manager to analyze the risk impact scale as to the schedule, cost and quality, and to distinguish priority via probability and impact data elements that lead to rating the risks as low, moderate, or high priority [32]. Furthermore, the most important component of the quantitative risk analysis process is the risk priority. To summarize, the goal of both of these procedures is to avoid the project manager from assessing individual risk events only, based on previous experience and intuition by giving numeric values. Therefore, by utilizing the project risk ontology, the study proposed another approach to conduct the numeric analysis of project risk.

As mentioned earlier, the risk classification could aid the project manager to identify the possible risks. Therefore, the project risk ontology could support to identify the project risks distinguished by the risk categories, subclasses and indexes. Consequently, the amounts of identified risk could represent the quantities of project risk degree. However, the impact scales among these risks can fluctuate. Thus, the weights of each risk class and subclass were required to quantitatively measure the severity of project risk degree.

The first step in establishing the risk numeric analysis model was to set up risk class and subclass weight. Based on the risk classification, the following step was to set the weight of each risk subclass and risk class to the influence of each project goal, i.e., cost, time, and quality. To capture the experts' experience and assessment on risk categories and subclasses, this study found the Analytical Hierarchy Process (AHP) was ideal to this step. The AHP method assists in making both qualitative and quantitative decisions. From the literature, the AHP method has been adopted widely in decision making among construction industry [45,11,1]. Therefore, this study adopted the AHP questionnaire to set the weights of each risk class and subclass by acquiring the tacit risk knowledge.

To represent project risk by numerical rating, a risk quantitative assessment method was required. Accordingly, project risk evaluation criterion was established, according to the risk indexes for each risk event established in the Section 4.5 . Furthermore, these evaluation criterions could also help PM to identify the possible risk when it was used as a risk checklist. Thus, this solution could integrate the procedures of risk identification and risk analysis.

Following the development of risk indexes, the ORM framework was built as illustrated in Fig. 2. By using the evaluation framework above, the user could evaluate severity of each risk event with reference to evaluation criterions (see Fig. 2). Therefore, each risk event would have numerous evaluation criterions, and the total risk score of each risk event would be the total number of the criterions that are met. The user

could review and obtain the risk score of each individual risk event through the evaluation criterions, as shown in step 1 in Fig. 2. Subsequently, the user could calculate severity of each risk event according to weight obtained from AHP, as shown in step 2 in the Diagram. The calculation formula for the risk severity was as follows:

$$\text{Risk value of risk event} = \sum_{i=1}^n \text{Risk scores of risk event} * \text{weight of risk event} \tag{1}$$

Taking External risk categories as the example, the calculation formula for ERVt is $ERV_t = \sum_{i=1}^4 ERV_i = \sum_{i=1}^4 ERS_i * ERW_i$ (ERS was risk score of individual risk event; ERW was risk weight of individual risk event; ERVt was the overall risk score for all risk categories).

More importantly, the user could adopt the weight of each risk class to calculate the overall risk score for the entire project, that is, Project Risk Index (PRI), as shown in step 1, and to evaluate the overall risk for the project, accordingly. The calculation formula for PRI was as follows:

$$PRI = \sum_{i=1}^8 \text{Risk value of risk c; ass} * \text{weight of risk class} \tag{2}$$

Where:

$$\text{Risk value of risk class} = \sum_{i=1}^n \text{Risk scores of risk event} * \text{weight of risk event}$$

For the aspect of PRI application, this risk numeric analysis model could support PM to assess the overall risk of the project and risk distribution via PRI value. Moreover, the contractor could also obtain project risk situation through the analysis of time series on overall PRI that was calculated from the project's inception. The contractor could accumulate and calculate PRI values of different types of projects to construct a standard for aiding in decision-making on RM in the future. Therefore, the organization could adopt the calculation of PRI value and the comparison of the historical figures to monitor and evaluate the overall risk. To summarize, the project manager could gain an understanding of the overall risk value of project risk and risk situation of individual risk type via the model. Therefore, the model

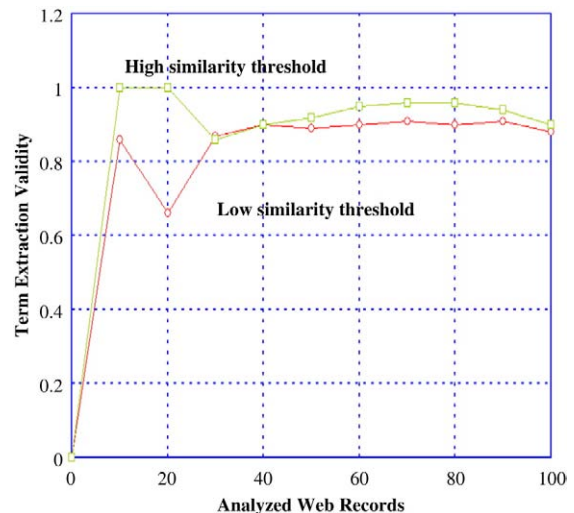


Fig. 5. Terms extraction validity test result for dynamic ontology extraction tool.

could not only help the project manager conduct risk quantitative assessment, but calculate risk and decide the risk response priority, as well. Moreover, by combining explicit knowledge extracted and the expert's tacit knowledge, the ORM framework could improve the risk knowledge reuse.

4.7. Establishment of the dynamic ontology extraction tool

From the literatures, the development of ontology requires a great deal of time, cost, and expertise. In this study, the project risk ontology development also involved many expert interviews and document analysis. Therefore, the update of ontology became the critical research issue to maintain the usability of ontology. To address this issue, the study developed the dynamic ontology extraction tool to supplement and renew the ontology. Thus, the prototype of the IR algorithm-based dynamic risk profile analysis tool was developed.

IR models were developed to provide the analytical ability to measure document relevancies [23]. Through using IR algorithms, it could help the document summarization by extracting important terms [52]. Hence, the document could represent as a set of important term vectors. In IR research domain, these important terms are also called a set of semantically relevant keywords. Moreover, the document relevancies were calculated based on these important terms. Subsequently, the relevancy of documents could be decided by the Vector model. In the Vector model, two documents would transfer into two individual vectors in virtual space.

In this study, the proposed dynamic ontology extraction tool was focused in the extraction of important risk concepts. Therefore, the study changes the document relevancy calculation model from the document view into the keyword view, as illustrated in Fig. 4. In the keyword view vector-space, this study adopted a document vectors set to identify keywords. The keyword relevancies can be decided by the same Vector model. Hence, the relation between risks can be determined by this

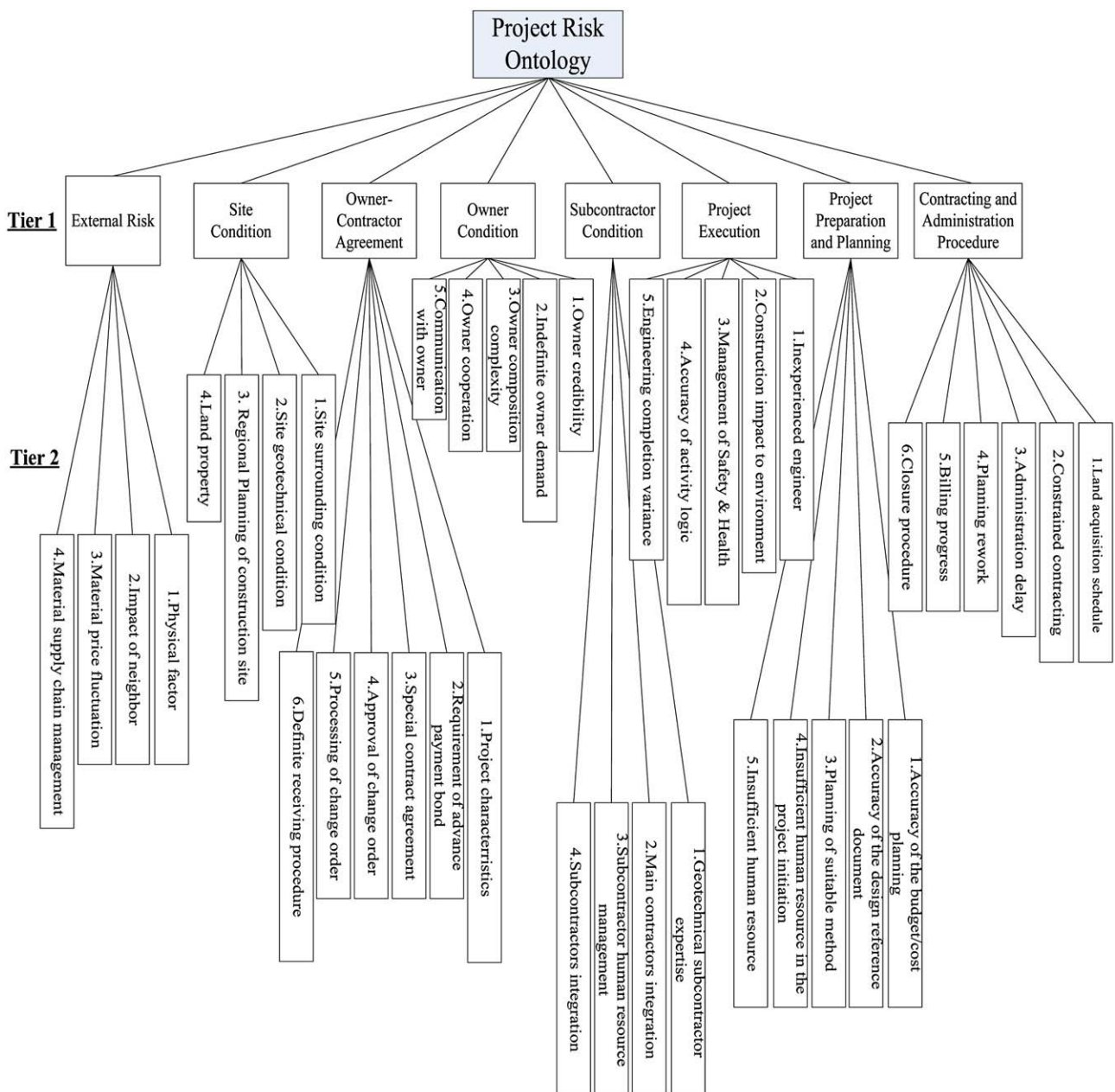


Fig. 6. Hierarchy framework of the project risk ontology.

Table 3
AHP weights of risk categories and risk subclasses for the selected contractor.

Risk category	Risk weight	Risk weight of each risk subclass
Site condition (SC)	0.078	Subclass 1: 0.173; Subclass 2: 0.115; Subclass 3: 0.345; Subclass 4: 0.368
Owner–contractor agreement (OA)	0.103	Subclass 1: 0.102; Subclass 2: 0.070; Subclass 3: 0.170; Subclass 4: 0.215; Subclass 5: 0.231; Subclass 6: 0.212
Owner condition (OC)	0.185	Subclass 1: 0.220; Subclass 2: 0.233; Subclass 3: 0.118; Subclass 4: 0.204; Subclass 5: 0.226
Subcontractor condition (SuC)	0.104	Subclass 1: 0.280; Subclass 2: 0.260; Subclass 3: 0.135; Subclass 4: 0.325
Project execution (PE)	0.189	Subclass 1: 0.122; Subclass 2: 0.226; Subclass 3: 0.311; Subclass 4: 0.228; Subclass 5: 0.112
Project preparation and planning (PP)	0.147	Subclass 1: 0.162; Subclass 2: 0.224; Subclass 3: 0.333; Subclass 4: 0.168; Subclass 5: 0.112
Contracting and administration procedure (CA)	0.121	Subclass 1: 0.129; Subclass 2: 0.128; Subclass 3: 0.196; Subclass 4: 0.293; Subclass 5: 0.163; Subclass 6: 0.090
External risk (ER)	0.073	Subclass 1: 0.128; Subclass 2: 0.108; Subclass 3: 0.439; Subclass 4: 0.324

Vector model. Through the timely analysis of IR algorithm, the ontology extraction tool can support the dynamic update of ontology.

In this Vector model, the similarity between two keywords (risk concepts) can be measured by the closeness of two keyword vectors. From the literature, the similarity can be calculated by cosine value of two keyword vectors: kw^i and kw^j , as in Eq. (6) [14]. Eqs. (3)–(5) define the term weighting calculation of each keyword. Moreover, the coefficient 0.5 was used to normalize the term frequency proposed by Salton and Buckley [13].

$$W_{dj, kw} = \left(0.5 + 0.5 \times tf_{dj, kw}\right) \times idf_{kw} \quad (3)$$

$$= \left(0.5 + 0.5 \times \frac{fre_{kw}}{\max fre}\right) \times \log \frac{N}{n_{kw}}$$

$$tf_{dj, kw} = \frac{fre_{kw}}{\max fre} \quad (4)$$

$$idf_{kw} = \log \frac{N}{n_{kw}} \quad (5)$$

$$similarity\left(\vec{kw}^j, \vec{kw}^k\right) = \cosine\left(\vec{kw}^j, \vec{kw}^k\right) \quad (6)$$

$$= \frac{\sum_{i=1}^n W_{di, kwj} \times W_{di, kwk}}{\sqrt{\sum_{i=1}^n W_{di, kwj}^2} \times \sqrt{\sum_{i=1}^n W_{di, kwk}^2}}$$

Where:

$W_{di, kw}$ is the term weight of keyword kw in document d_i ; fre_{kw} is the frequency of each keyword; $\max fre$ is the maximum frequency of keyword kw in document d_i ; $\sum_{i=1}^{sj} fre$ is the total frequency of all keywords in each document; N is the total document numbers of knowledge base; n_{kw} is the total numbers of document in which certain keyword appears.

Based on this IR algorithm, this study developed the prototype of ontology extraction tool. Through the deployment of IR algorithms, this tool can process text as follows: (1) document cleaning; (2) keyword extraction; and (3) selection of the important keyword (risk concept). In this study, the document cleaning work included the removing of stop-words and affixes. Moreover, this tool replaced the synonyms with the same term in the analyzed text based on the thesaurus developed in the Section 4.4. Through these steps, the tool can extract the most important risk concept based on the correct frequency of term appearances. And the prototype (Prototype A) was built up by integrating the Chinese extraction module, the document cleaning module, the similarity calculation module, and a user interface.

The ontology extraction tool was designed to dynamically extract important risk concepts and hence supplement the project risk ontology. Therefore, the terms extraction validity must be confirmed. In this step, the study adopted the valid lexicons extracted rate to test the validity of the ontology extraction tool. Moreover, the study used the web record to test the terms extraction validity. The equation for the terms extraction validity was as below:

$$\text{Terms Extraction Validity} = \frac{\text{Valid Lexicons Extracted}}{\text{Total Lexicons Extracted}} \quad (7)$$

In the validation for prototype, the study randomly selected 100 web records to measure the performance of the tool. Moreover, the study used 2 term similarity threshold, including: low similarity threshold (0.70) and high similarity threshold (0.90) to test the terms extraction validity. The results of this testing was illustrated in Fig. 5. From the testing, the valid lexicons extracted rate was mostly over 80% for both similarity thresholds. Moreover, the high similarity threshold could derive better extraction performance. Through the testing of the prototype, the performance of the ontology extraction tool was proved.

5. Case demonstration

To validate the effectiveness of the ORM framework, this study implemented the ORM framework for actual construction projects. The case study of this study was derived from the Ruentex Construction & Engineering Company established in 1977 in Taiwan, which was a rare enterprise with a strong integration-ability of horizontal and vertical levels. There are 500 employees in the entire enterprise. The business scope includes construction, design, precast, mechanical, interior design, building security service, elder caring and nursing home, real-estate, etc. This general builder began to develop its management information system in 1983, and began an evaluation on the ERP implementation in June 2001. Moreover, the selected contractor had implemented the PMBOK project management approach and the web-based RM system as the ICT solution of the project RM workflow in 2004. The scope of the implementation included: (1) the development of project risk ontology; (2) the extraction of the risk knowledge base; (3) the implementation of the proposed ORM approach; and (4) the modification of the dynamic ontology extraction tool. Subsequently, this study conducted an interview with the selected contractor's project managers to confirm the

Table 4
Consistency ratio (C.R.) of each risk category of the selected contractor.

Risk category	C.R.
Site condition (SC)	0.01
Owner–contractor agreement (OA)	0.01
Owner condition (OC)	0.012
Subcontractor condition (SuC)	0.004
Project execution (PE)	0.013
Project preparation and planning (PP)	0.022
Contracting and administration procedure (CA)	0.037
External risk (ER)	0.01

feasibility and modification of the ORM framework application. Moreover, this study evaluated the ORM framework in terms of the management-level interview results. Finally, the study also held an expert workshop to discuss and validate this framework.

5.1. Definition of scope

Through the implementation of the POKM model and the PMBOK project management approach, the contractor knowledge base in the

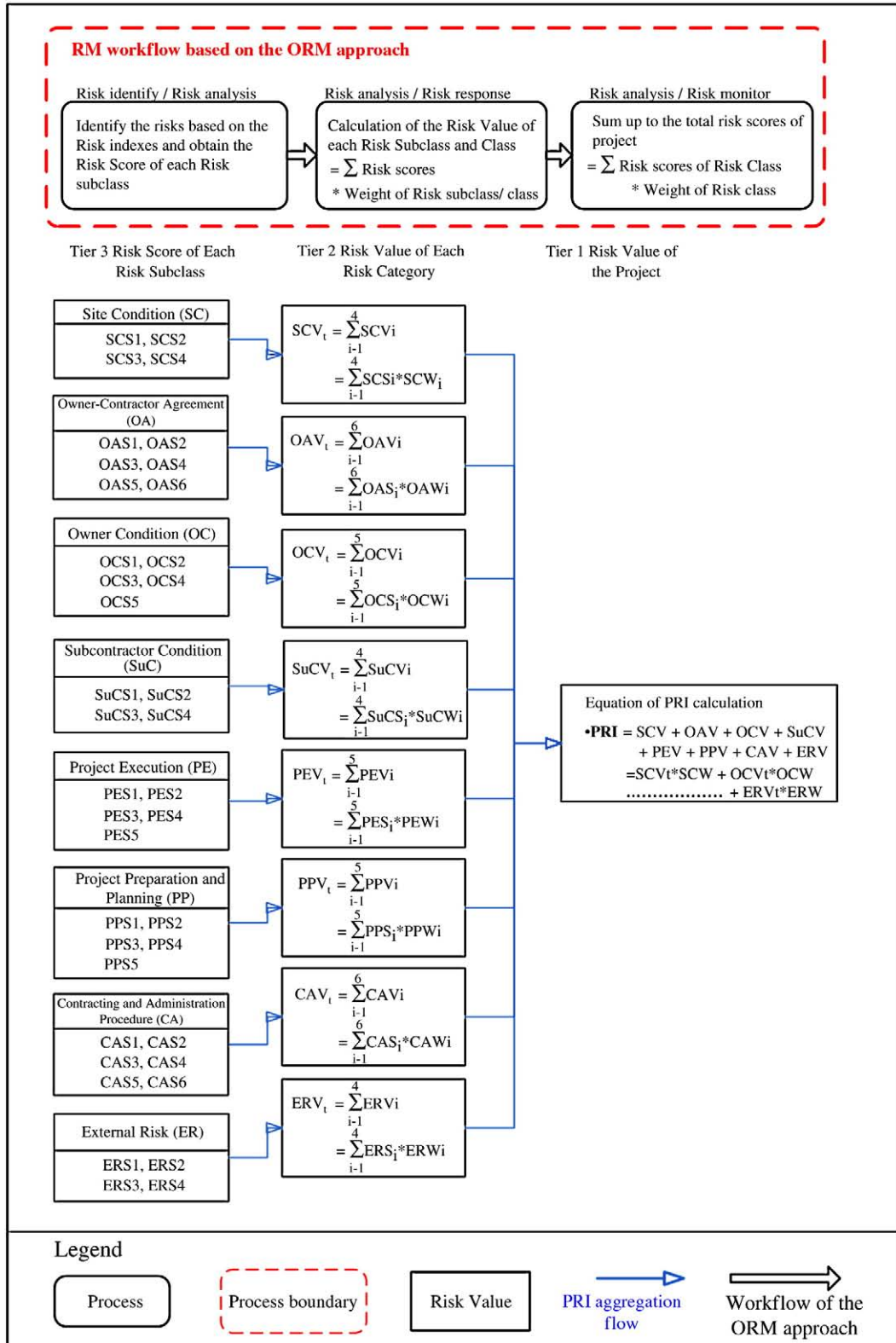


Fig. 7. Development of the project risk quantitative analysis model.

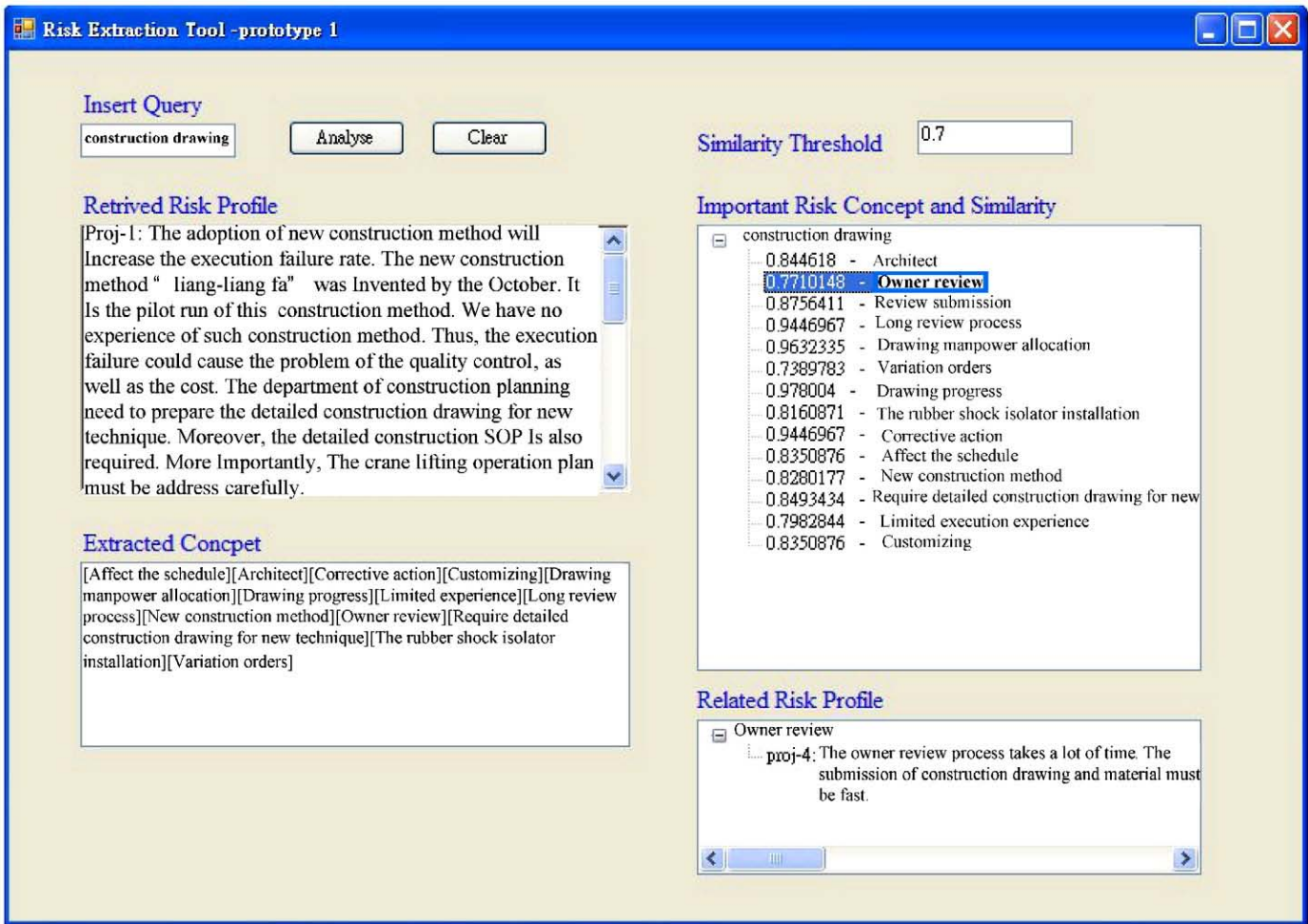


Fig. 8. Screen shot of the dynamic ontology extraction tool.

previous research provides a strong foundation for the knowledge extraction and ontology development. Therefore, this study adopted this knowledge base as the resource for the knowledge extraction.

As discussed earlier, analysis of knowledge demand of RM workflow shapes and defines the scope for the ontology development. Therefore, the study conducted the interview with the RM team of the selected contractor to identify the possible knowledge source of ontology development based in the Table 2. From the interview, the study identified the risk data base of the web-based RM system and the risk classification would be the main sources for the project risk ontology development.

5.2. Requirement collection

For the selected contractor, although it had implemented the KM in the RM workflow, the entire RM workflow still lacked an assessment model for risk quantitative analysis to support the RM decision making. In addition, the selected contractor lacked an integrated risk monitor and assessment tool. For these objectives, this study assisted the selected contractor in implementing the ORM framework to overcome the aforementioned problems.

5.3. Extraction of important concepts for risk ontology

As discussed earlier, a variety of methods could be used to extract important concepts from the target domain. In this step, this study adopted document analysis as the major concept extraction method.

To establish the knowledge database for concept extraction, this study gathered risk knowledge on construction projects. First, this study conducted a survey of typical risk events in each functional departments of the selected contractor, i.e., procurement, construction planning. In this step, 132 risk types were built from 8 functional departments. Second, this study would assemble the risk profiles of the risk knowledge base. The risk profiles consisted of risk events, including: risk event description, cause, consequence, response, risk status, and qualitative analysis. Subsequently, all project managers (PM) and functional department managers within the organization

Table 5

The similarity calculation result of the test retrieval.

Related risk concept	Similarity ^a
Affect the schedule	0.8350876
Architect	0.844618
Corrective action	0.9446967
Customizing	0.8350876
Drawing manpower allocation	0.9632335
Drawing progress	0.978044
Limited experience	0.7982844
Long review process	0.9446967
New construction method	0.8280177
Owner review	0.7710148
Require detailed construction drawing for new technique	0.8493434
The rubber shock isolator installation	0.8160871
Variation orders	0.7389783

^a A query-related concept similarity value obtained by Eq. (6).

Table 6
Test retrieval results for Prototype B.

No.	Query	Analyzed relevant risk profile	Relevant extracted risk concepts	Extracted risk concepts	Relevant risk concepts	Precision (%)	Recall (%)
1	Construction diagram	6	17	19	21	89	81
2	Construction Site Condition	13	15	18	18	83	83
3	Owner Condition	16	29	35	34	83	85

were requested to conduct the survey of risk events concerning their current respective projects. Through this procedure, the initial knowledge database of 115 risk profiles among 13 projects was established while the risk experiences were compiled and clearly documented. After converging the relevant risk knowledge and information, the analysis of risk profiles was performed. Hence, a preliminary set of concepts was established. The set of approximately 500 concepts emerged.

Following the completion of the preliminary set, the study refined it through expert interviews. In this study, 5 project managers with an average of 21 years of working experience from the selected contractor were interviewed. These managers were chosen because they are the RM experts in the major project types in this selected contractor. In this case study, the major project types are high-tech factory, residential building and office. Following the interviews, the preliminary set was refined again into approximately 200 concepts. In addition, a thesaurus of project risks was also established for a further information retrieval operation. Thus, in this stage, the extraction of explicit knowledge was completed.

5.4. Development of the project risk ontology

Following the basic taxonomies of ORM framework, the risk concepts could be organized into risk classification. By RM operation scenario, the risk classification framework could be applied to risk identification; therefore, the basic risk taxonomies needed the modification for the selected contractor. To address this issue, the study collaborated with the RM team to modify the basic risk taxonomies. Moreover, in this step, the same respondents (those five managers mentioned in Section 5.4) were interviewed again. To

further analyze project risk, this study established a cause-and-effect diagram for the purpose of project risk analysis. In this phase, as demonstrated in Fig. 6, this study determined 8 risk categories, 39 risk subclasses and 195 risk indexes in the third tier.

Furthermore, to the issue of the iterative development of ontology, the study also held a senior managers' workshop, consisting of the heads of each department and senior managers to discuss the hierarchical risk classification. In this workshop, 6 senior managers or engineers with an average of 30-years of working experience reviewed and modified this hierarchical risk classification.

5.5. Implementation of the ORM approach

The first step in establishing the risk numeric analysis model was to set up risk class and subclass weight. Therefore, this study designed the AHP questionnaire to conduct full pair-wise comparison on all risk categories and all risk subclasses in each risk category. The hierarchy framework of the questionnaire was shown in Fig. 6.

The questionnaire was designed for those project managers who had been working for the selected contractor for over 15 years and had profound experience with the construction industry. A total of 25 questionnaires were disseminated to the subjects: 20 completed questionnaires were returned from the subjects, and used in this study. Because the questionnaire was complicated, the subjects' responses to the questionnaires were answered by telephone interview or face-to-face discussion. After the completion of questionnaire analysis, this study set AHP weights for each risk category and risk subclasses of each risk category, as illustrated in Table 3.

Next, Reliability Analysis was conducted to ensure the reliability of the questionnaire results. For reliability analysis, Consistency Analysis was used to judge the reliability of each expert's assessment based on Consistency Ratio (C.R.) when $C.R. < 0.1$. This study used Consistency Analysis to analyze each hierarchy and overall hierarchy. The result represented Consistency Index of overall hierarchy (C.I.H.) was 0.0278 and consistency ratio of the overall hierarch (C.R.H.) was 0.0255. It could be found that $C.R.H. < 0.1$, therefore, consistency of overall hierarchy was acceptable. Otherwise, consistency checking for each hierarchy stated the same result, as presented in Table 4.

Based in the survey results and the project risk ontology, the project risk quantitative analysis model of the ORM framework was built, as illustrated in Fig. 7. Subsequently, the project managers could calculate the risk values for risk events, classes and overall risk score

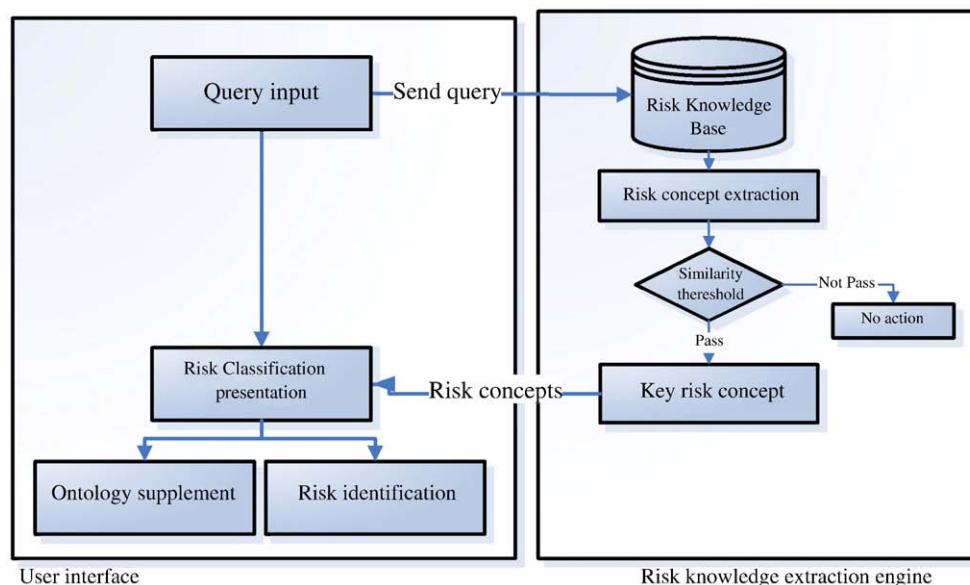


Fig. 9. Operation mechanism of the dynamic ontology generate tool.

for the entire project (PRI). In particular, this study, along with the selected contractor, conducted tacit knowledge acquisition within the organization via the result of this AHP questionnaire. The outcome could not only establish the base for quantitative assessment model, but also help the project manager judge the management priority of risk events in the project.

5.6. Implementation and evaluation of the dynamic ontology extraction tool

Among the ORM framework, the ontology extraction tool was designed to dynamically extract important risk concepts and hence supplement the project risk ontology. To address this issue, the study collaborated with the RM team to design the using scenario of the tool. According to the characteristics of project risks, the risk classes and subclasses are static, while the risk indexes are much more dynamic and require the continuous update by the RM team. Thus, for the selected contractor, the tool was designed to retrieve these concepts based on the risk subclass and any important risk concept. The prototype (Prototype B) for the selected contractor was built up by the Prototype A (see Fig. 8).

As shown in Fig. 8, the study used the query “construction drawing” to retrieve the related risk concept in this test retrieval. Subsequently, the related risk concepts were retrieved by this tool. Moreover, the relation between retrieved risk concept and risk query could be identified through the similarity calculation as illustrated in Table 5. In this test retrieval, the similarity threshold was set to 0.70 (low similarity threshold) to avoid the missing of important risk concepts. And such threshold number could be modified through further test trial by the selected contractor. In this test retrieval, the risk concept “Drawing manpower allocation” was highly related to the query. And the detailed calculation was shown as below:

$$\text{similarity} \left(\text{query}^j, \text{drawing - manpower}^k \right) = \frac{\sum_{i=1}^n W_{di, kvj} \times W_{di, kvk}}{\sqrt{\sum_{i=1}^n W_{di, kvj}^2} \times \sqrt{\sum_{i=1}^n W_{di, kvk}^2}} = \frac{4.966549}{5.15612} = 0.9632335$$

According to this test retrieval, the risk concept “drawing manpower allocation” was the most important risk in the timely project risk nature of the case study company. Moreover, to validate the extraction performance of risk concept, 3 test retrievals were conducted to provide the measurement of the extraction validity. Table 6 listed the extraction performance of the test retrievals. In these tests, 35 risk profiles were retrieved from the risk knowledge base. The knowledge base composed of 115 risk profiles was built up from 2005 to 2006. Due to this tool focused on extracting risk concepts than the

retrieval of relevant risk profiles, the precision and recall rate [8] were adopted and modified to evaluate the extraction performance of the proposed tool as below:

$$\text{Precision} = \frac{\text{Relevant Extracted Risk Concepts}}{\text{Extracted Risk Concepts}} \tag{8}$$

$$\text{Recall} = \frac{\text{Relevant Extracted Risk Concepts}}{\text{Relevant Concepts}} \tag{9}$$

From the testing, the average precision and recall rate were over 80% and accepted by the selected contractor. Furthermore, the other dynamically extracted risk concepts could filter by similarity threshold or expert judgements. Afterwards, the retrieval result could provide the possible risk indexes to supplement the original risk indexes. Thus, this dynamic information could help the identification of possible risk and supplement of project risk ontology. To summarize, the mechanism to use this tool is illustrated in Fig. 9.

5.7. Filed trial evaluation

After the implementation of the ORM framework, the study verified the ORM framework through 5 construction projects of the selected contractor including 2 high-tech factories, 2 residential buildings and 1 office building. These projects were the most typical project of the selected contractor. The project managers of these 5 projects used the ORM framework ranging from risk identification, risk analysis, to conducting further project risk analysis and planning.

Table 7 listed the testing results of the filed trials. Following the adoption of this ORM framework, the project managers pointed out that project risks were identified through this framework accurately. Moreover, they also mentioned the risk score and severity could be determined simultaneously by applying the AHP weights of risk classes and subclasses. Hence, this framework could facilitate risk identification, analysis, and response procedures. The field trial results proved that risk values and distributions calculated from the ORM framework could reflect the project status based on PRI calculation. Through the implementation of the ORM approach, these project managers could employ the accurately responses with the correct priority setting. Therefore, the project risks were effectively handled. The Project RM performance measurements were demonstrated in Table 8. Moreover, in addition to proving that the model could help PM identify and monitor project risk, the outcome also verified the effectiveness of the project risk ontology development model.

Furthermore, the study held a domain expert workshop to discuss the ORM framework and the test case studies. In this study, 6 domain experts with an average of 25-years of working experience were interviewed. The workshop began with 20 min presentation about the ORM framework development and the case study, and the experts

Table 7
Test results of the project risk quantitative assessment model.

Project	Project type	Contract budget ^a (US dollar)	Risk value of each risk category				PRI	Evaluation
A	High-tech factory	\$10,303,030	SCVt 1.909	OCVt 1.524	OAVt 2.318	SuCVt 2.695	2.329	Accurate identification and analysis of project risk
			PEVt 2.995	CAVt 1.74	PPVt 2.77	ERVt 2.673		
B	High-tech factory	\$696,969	SCVt 3.197	OCVt 0.118	OAVt 0.482	SuCVt 1.195	1.035	Accurate identification and analysis of project risk
			PEVt 0.228	CAVt 1.363	PPVt 1.712	ERVt 1.782		
C	Office	\$16,515,151	SCVt 1.403	OCVt 0.555	OAVt 0.312	SuCVt 0.27	0.861	Accurate identification and analysis of project risk
			PEVt 0.808	CAVt 0.971	PPVt 1.326	ERVt 1.694		
D	Residential building	\$4,490,606	SCVt 2.347	OCVt 1.123	OAVt 2.495	SuCVt 1.56	1.567	Accurate identification and analysis of project risk
			PEVt 1.119	AVt 1.677	PPVt 1.88	ERVt 0.911		
E	Residential building	\$42,606,060	SCVt 2.8757	OCVt 0.57	OAVt 0.964	SuCVt 0	1.092	Accurate identification and analysis of project risk
			PEVt 1.449	CAVt 0.715	PPVt 1.45	ERVt 1.235		

^aThe currency exchange rate: 1 US dollar = 33 Taiwan dollar.

Table 8

Project RM performance measurement of the field trials.

Project	Project RM performance measurement		
	Time	Cost	Quality
A	Project delivered on time	No cost increasing	Only very demanding applications are affected
B	Project delivered on time	2% cost increasing	Only very demanding applications are affected
C	Project delivered on time	Insignificant cost increasing	Quality was acceptable
D	<5% time increasing	No cost increasing	Only very demanding applications are affected
E	Project delivered on time	Insignificant cost increasing	Quality was acceptable

were then asked to provide the suggestion and inquiries. The major suggestions are summarized below:

1. The ORM framework could reduce the complexity of common RM workflow effectively, especially via the risk analysis stage of the process. Moreover, inexperienced engineers could adopt the framework easily when conducting decision-making.
2. The ORM framework could help contractors to transfer organization knowledge to handle the project risks better. Moreover, the tacit knowledge could record and apply to the subsequent projects.
3. The ORM framework and the ontology development model are solid and could apply in other RM field such as disaster handling and earthquake risk management. They also suggested future research could work in these fields to extend the application field of the proposed framework.

6. Conclusion

This ORM framework aimed to verify the project risk ontology could enhance RM workflow performance within the construction organization by case study, and hence decrease risk impact on the project. Through the implementation of the ORM framework and the ontology development model, the selected contractor could integrate knowledge reuse in the RM operation. Consequently, based on knowledge accumulation and reuse, the aforementioned RM problems could also be overcome and hence support the RM decision making.

The study attempted to propose a knowledge extraction model that was applicable to construction project risk ontology development. Through literature review, the study analyzed the relevant approaches proposed by previous studies and the characteristics of construction RM. After considering the requirements of construction RM workflow, the study adopted the expert interview and AHP approach to establish the ontology. Moreover, the IR algorithm-based ontology extraction tool was developed to supplement the ontology. To summarize, this study proposed 1) project risk ontology development model, and 2) risk knowledge extraction model of ORM framework.

By case study, this study proved that the ORM framework could help the contractor conduct knowledge reuse during RM procedures to decrease risk threats to the project. Simultaneously, the outcome also confirmed the effectiveness when project risk ontology was applied to construction RM workflow. Through knowledge extraction and reuse, the organization could not only manage project risk more efficiently, but, also disseminate the organization risk knowledge effectively. Moreover, the contractor could decrease RM workflow complexity and increase organization RM effectiveness via this ORM framework.

In addition, the study validated that through the mechanism of extracting explicit knowledge and acquiring tacit knowledge, these two types of knowledge could be combined and applied to workflow. Based on ORM framework, the organization could adopt the approach to enhance workflow performance. Moreover, different from the previous deficiencies, the approach could assist the organization in acquiring and reusing tacit knowledge when applying KM.

With regard to application of the ORM framework and the ontology development model to other construction practitioners, the model was proposed with reference to typical RM standard procedure and knowledge application scenario. Moreover, the ORM

framework was validated through case study verification and extensive domain expert interviews. Therefore, the construction practitioners could apply this ORM framework to establish project risk ontology and enhance RM performance through knowledge reuse.

References

- [1] A. Pandit, Y. Zhu, An ontology-based approach to support decision-making for the design of ETO (Engineer-To-Order) products, *Automation in Construction* 16 (6) (2007) 759–770.
- [2] A.S. Akintoye, M.J. MacLeod, Risk analysis and management in construction, *International journal of project management* 15 (1) (1997) 31–38.
- [3] A.S. Ang, D.D. Leon, Modeling and analysis of uncertainties for risk-informed decisions in infrastructures engineering, *Structure and Infrastructure Engineering* 1 (1) (2005) 19–31.
- [4] A.R. Mohamed Eshaq, P. Karboulonis, Design considerations for the design of an advanced VR interface for knowledge management and its relevance to CAD, *Automation in Construction* 12 (5) (2003) 501–507.
- [5] B.H.W. Hadikusumo, Steve Rowlinson, Capturing safety knowledge using design-for-safety-process tool, *Journal of Construction Engineering and Management* 130 (2) (2004) 281–289.
- [6] B. Kosovac, T.M. Froese, D.J. Vanier, Integrating heterogeneous data representations in model-based AEC/FM systems, *Proc. CIT '00*, vol. 2, IABSE, 2000, pp. 556–567, Reykjavik, Iceland.
- [7] B. Mulholland, J. Christian, Risk assessment in construction schedules, *Journal of construction engineering and management* 125 (1) (1999) 8–15.
- [8] B.Y. Ricardo, R.N. Berthier, *Modern information retrieval*, Addison Wesley, New York, 1999.
- [9] C.H. Caldas, L. Soibelman, J. Han, Methodology for the integration of project documents in model-based information systems, *Journal of Computing in Civil Engineering* 19 (1) (2005) 234–243.
- [10] D.K.H. Chua, Y.M. Goh, Incident causation model for improving feedback of safety knowledge, *Journal of Construction Engineering and Management* 130 (4) (2004) 542–551.
- [11] F.M. Arain, L.S. Pheng, Knowledge-based decision support system for management of variation orders for institutional building projects, *Automation in Construction* 15 (3) (2006) 272–291.
- [12] G. Carter, S.D. Smith, Safety hazard identification on construction projects, *Journal of Construction Engineering and Management* 132 (2) (2006) 197–205.
- [13] G. Salton, C. Buckley, Term-weighting approaches in automatic retrieval, *Information Processing & Management* 24 (5) (1988) 513–523.
- [14] G. Salton, *Automatic Text Processing: The Transformation, Analysis, and Retrieval of Information by Computer*, Addison Wesley, New York, 1989.
- [15] H.C. Tan, P.M. Carrillo, C.J. Anumba, N. Bouchlaghem, J.M. Kamara, C.E. Udeaja, Development of a methodology for live capture and reuse of project knowledge in construction, *Journal of management in engineering* 23 (1) (2007) 18–26.
- [16] I. Dikmen, M.T. Birgonul, C. Anac, J.H.M. Tah, G. Aouad, Learning from risks: a tool for post-project risk assessment, *Automation in construction* 18 (1) (2008) 42–50.
- [17] I. Nonaka, The concept of 'Ba': building a foundation for knowledge creation, *California Management Review* 40 (3) (1998) 40–54.
- [18] J.H.M. Tah, V. Carr, Knowledge-based approach to construction project risk management, *Journal of Computing in Civil Engineering* 15 (3) (2001) 170–177.
- [19] J. Raftery, *Risk Analysis in Project Management*, E&FN SPON, New York, 1994.
- [20] J.H. Woo, M.J. Clayton, R.E. Johnson, B.E. Flores and C. Ellis, Dynamic Knowledge Map: reusing experts' tacit knowledge in the AEC industry, *Automation in construction* 13(2) (2004) 203–207.
- [21] K.J. Yi, D. Langford, Scheduling-based risk estimation and safety planning for construction projects, *Journal of construction engineering and management* 132 (6) (2006) 626–635.
- [22] K.R. Nielsen, Risk management: lessons from six continents, *Journal of management in engineering* 22 (2) (2006) 61–67.
- [23] K.Y. Lin, L. Soibelman, Promoting transactions for A/E/C product information, *Automation in Construction* 15 (6) (2006) 746–757.
- [24] M. Nissen, M. Kamel, K. Sengupta, Integrated analysis and design of knowledge systems and processes, *Information Resources Management Journal* 13 (1) (2000) 24–43.
- [25] M.W. McElroy, *The New Knowledge Management: Complexity, Learning, and Sustainable Innovation*, KMCI Press/Butterworth-Heinemann, Burlington, 2003.
- [26] N.A. Kartam, S.A. Kartam, Risk and its management in the Kuwaiti construction industry: a contractors' perspective, *International journal of project management* 19 (6) (2001) 325–335.

- [27] O.A. Jannadi, S. Almishari, Risk assessment in construction, *Journal of construction engineering and management* 129 (5) (2003) 492–500.
- [28] Organization for Economic Co-operation and Development, *The Knowledge-based Economy*, Paris, 1996.
- [29] P. Carrillo, P. Chinowsky, Exploiting knowledge management: the engineering and construction perspective, *Journal of Management in Engineering* 22 (1) (2006) 2–10.
- [30] P. Demian, R. Fruchter, CoMem: evaluating interaction metaphors for knowledge reuse from a corporate memory, CIFE Technical Report, Stanford University, June 2004.
- [31] P.F. Drucker, *Post-capital Society*, Harper Collins, New York, 1993.
- [32] Project Management Institute (PMI), *A guide to the project management body of knowledge (PMBOK guide)*, PMI Inc., Pennsylvania, 2004.
- [33] R.V. Wyk, P. Bowen, A. Akintoye, Project risk management practice: the case of a South African utility company, *International journal of project management* 26 (2) (2008) 149–163.
- [34] R.H. Clough, C.A. Sears, S.K. Sears, *Construction Project Management*, 4th edR, Wiley, New York, 2000.
- [35] S. Baradan, M.A. Usman, Comparative injury and fatality risk analysis of building trades, *Journal of construction engineering and management* 132 (5) (2006) 533–539.
- [36] T.E. El-Diraby, B. Wang, E-society portal: integrating urban highway construction projects into the knowledge city, *Journal of Construction Engineering and Management* 131 (11) (2005) 1196–1211.
- [37] T.E. El-Diraby, F. Briceno, Taxonomy for outside plant construction in telecommunication infrastructure: supporting knowledge-based virtual teaming, *Journal of Infrastructure System* 11 (2) (2005) 110–121.
- [38] T.E. El-Diraby, C. Lima, B. Feis, Domain taxonomy for construction concepts: toward a formal ontology for construction knowledge, *Journal of Computing in Civil Engineering* 19 (4) (2005) 394–406.
- [39] T.H. Davenport, L. Prusak, *Working Knowledge, How Organizations Manage What They Know*, Harvard Business School Press, Boston, 1998.
- [40] T.H. Davenport, S.L. Jarvenpaa, M.C. Beers, Improving knowledge work process, *Sloan Management Review* 37 (4) (1996) 53–65.
- [41] T. Lyons, M. Skitmore, Project risk management in the Queensland engineering construction industry: a survey, *International journal of project management* 22 (1) (2004) 51–61.
- [42] T. Mezher, M.A. Abdul-Malak, I. Ghosn, M. Ajam, Knowledge management in mechanical and industrial engineering consulting: a case study, *Journal of Management in Engineering* 21 (3) (2005) 138–147.
- [43] T.E. El-Diraby, J. Zhang, A semantic framework to support corporate memory management in building construction, *Automation in Construction* 15 (4) (2006) 504–521.
- [44] T.E. El-Diraby, Web-services environment for collaborative management of product life-cycle costs, *Journal of Construction Engineering and Management* 132 (3) (2006) 300–313.
- [45] T.M. Zayed, L.M. Chang, Prototype model for build-operate-transfer risk assessment, *Journal of management in engineering* 18 (1) (2002) 7–16.
- [46] T.R. Gruber, Toward principles for the design of ontologies used for knowledge sharing, *International Journal of Human-Computer Studies* 43 (5–6) (1995) 907–928.
- [47] M.D. Tsai, H.P. Tserng, The application of knowledge management in Taiwan construction industry, Proc., International Symposium on Automation and Robotics in Construction, IAARC, Jeju Island, Korea, 2004, pp. 183–187.
- [48] U. Remus, S. Schub, A blueprint for the implementation of process-oriented knowledge management, *Knowledge and Process Management* 10 (4) (2003) 237–253.
- [49] U. Schultze, Investigating the Contradictions in Knowledge Management, Proc., IFIP '98 WG8.2 & WG8.6 Joint Working Conf. on Information Systems: Current Issues and Future Changes, vol. 9, IFIP, 1998, pp. 155–174, Helsinki, Finland, ISBN 3 901 882 02 2.
- [50] W.C. Wang, J.J. Liu, S.C. Chou, Simulation-based safety evaluation model integrated with network schedule, *Automation in construction* 15 (3) (2006) 341–354.
- [51] Y. Mohamed, S. AbouRizk, Technical knowledge consolidation using theory of inventive problem solving, *Journal of Construction Engineering and Management* 131 (9) (2004) 993–1001.
- [52] Y. Rezgui, Ontology-centered knowledge management using information retrieval techniques, *Journal of Computing in Civil Engineering* 20 (4) (2006) 261–270.
- [53] Y.C. Lin, L.C. Wang, H.P. Tserng, Enhancing knowledge exchange through web map-based knowledge management system in construction: lessons learned in Taiwan, *Automation in Construction* 15 (6) (2006) 693–705.
- [54] Y.L. Yin, H.P. Tserng, M.D. Tsai, A model of integrating the cycle of construction knowledge flows: lessons learned in Taiwan, *Automation in Construction* 17 (5) (2008) 536–549.
- [55] T.R. Gruber, A translation approach to portable ontologies, *Knowledge Acquisition* 5 (2) (1993) 199–220.