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A Knowledge-Based Risk Management Tool for Construction Projects using Case-based Reasoning

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Abstract

Construction projects are often deemed as complex and high-risk endeavours, mostly because of their vulnerability to external conditions as well as project-related uncertainties. Risk management (RM) is a critical success factor for companies operating in the construction industry. RM is a knowledge-intensive process that requires effective management of risk-related knowledge. Although some research has already been conducted to develop tools to support knowledge-based RM processes, most of these tools ignore some critical features, such as live knowledge capture, web-based platform for knowledge sharing and effective case retrieval for learning from past projects. Moreover, several RM phases, such as risk identification, analysis, response and monitoring are not usually integrated. Thus, this study aims to bridge these gaps by developing a knowledge-based RM tool (namely, CBRisk) via case-based reasoning (CBR). CBRisk has been developed as a web-based tool that supports the cyclic RM process and utilises an effective case retrieval method considering a comprehensive list of project similarity features in the form of fuzzy linguistic variables. Finally, the developed tool was evaluated and validated by conducting black-box testing and expert review meeting. Results demonstrated that CBRisk has a considerable potential to enhance the effectiveness of RM in construction projects and may be used in other project-based industries with minimal modifications.

Keywords: *Artificial Intelligence, Machine Learning, Knowledge-based Risk Management, Risk Management, Knowledge Management, Case-based Reasoning, Web-based Tool*

1. Introduction

The dynamic, turbulent, and complex nature of the construction industry (CI) leads to high uncertainty in construction projects and may adversely affect the performance of construction companies if uncertainty is not properly managed. Risk management (RM), that involves identification of sources of uncertainty (risk identification), estimating the probability and impact of uncertain events/conditions on a project (risk analysis), generating response strategies, and finally, monitoring the risks during a project becomes a vigorous concept for construction companies.

PMBOK (2018) defines RM as a series of efforts undertaken to increase the probability and/or impact of positive risks and to decrease the probability and/or impact of negative risks. Given the fact that unmanaged risks have the potential to deviate projects from their initial objectives, PMBOK (2018) directly relates to the effectiveness of project RM to project success. In this respect, RM is perceived as one of the indispensable knowledge areas. APM (2019) perceives RM as a systematic process that allows individual risk events and overall risk to be understood and managed proactively. In the absence of effective RM, APM (2019) states that it would be a challenging issue to optimize project success for the management team.

RM is a knowledge-intensive process since RM generates a high amount of knowledge and utilizes this knowledge (Yildiz, Dikmen, Birgonul, Ercoskun, & Alten, 2014). PMBOK (2018) also underlines the importance of knowledge stemming from an individual's experience for RM. In this respect, knowledge-based RM has been advocated by many researchers to improve the effectiveness of companies' RM practices. Dikmen et al. (2008) used the term "learning from risk" to suggest "a knowledge-driven risk management process" and "focus on lessons learned" for better RM. Learning from risk necessitates creating, securing, capturing, coordinating, combining, retrieving, and disseminating the risk-related knowledge of the projects (H. P. Tserng & Lin, 2005). In practice, RM in the construction projects depends on tacit knowledge that is generally stored in the minds of individuals rather than corporate risk memory, which in turn may lead to loss of critical knowledge due to the high staff turnover in the industry. Therefore, effective exploitation of risk-related knowledge stored in corporate risk memory, such as lessons learned from previous projects about risk events, consequences, effectiveness of response strategies etc. is of vital importance. Corporate risk memory allows companies to update their risk management knowledge and eventually they may have precise and accurate forecasts about risks, likelihood of risk occurrence, as well as their consequences (Dikmen et al., 2008). Atkinson et al. (2006) also pinpointed that risk-related experience gained throughout the past projects is the fundamental necessity for accurate risk estimations. Although each project is a unique and temporary undertaking, they still have similar features such as the structure of teams, construction processes, tools/methods, and skills (Kamara, Anumba, Carrillo, & Bouchlaghem, 2003). Due to these similarities, the same problems seen in one project are likely to re-occur in forthcoming projects until an appropriate solution is implemented (Eken, Bilgin, Dikmen, & Birgonul, 2015). Consequently, the companies can perform more effective RM in forthcoming projects by constructing and utilising a corporate risk memory. In this way, it is ensured that the re-invention of the wheel at every project would be prevented. However, capturing risk knowledge during the past and/or current projects, and exploiting this knowledge during the life cycle of a current and/or forthcoming project is a challenging task for most construction companies (Kivrak, Arslan, Dikmen, & Birgonul, 2008).

Many researchers argued that construction companies can barely capture, store, and disseminate knowledge to optimize the RM of forthcoming projects (Alashwal & Abdul-Rahman, 2014; Fong, 2005). Although the benefits of knowledge-based systematic RM are widely discussed in the literature (Abu Bakar, Yusof, Tufail, & Virgiyanti, 2016; Chan, Cooper, & Tzortzopoulos, 2005; Vakola & Rezgui, 2000; Yang et al., 2014), implementation of these systems in practice is rather low among the construction companies due to the lack of learning culture and ineffective knowledge management (KM) processes/tools (Ford, Voyer, & Wilkinson, 2000; Kivrak et al., 2008; McLaughlin, Paton, & Macbeth, 2008; Steiner, 1998; Tan et al., 2010). In literature, efforts have been devoted by several authors to establish systematic knowledge-based RM tools such as Dikmen et al. (2008), Yildiz et al. (2014), and Fan et al. (2015). However, each tool or approach has its own assumptions and methodological drawbacks.

This study, therefore, aims to develop a web-based organizational learning tool that can be used for capturing, storing, retrieving, and disseminating risk-related knowledge. The tool has been designed to support all processes of RM and facilitate knowledge-based RM. In this study, as an artificial intelligent method, Case-based reasoning (CBR) has been used to develop the tool. CBR has been identified as an ideal and promising method to exploit risk-related knowledge from past projects (Lu, Li, & Xiao, 2013). The web-based tool, named "CBRisk", has the potential to be used by construction organizations to develop a corporate risk memory that can store risk-related knowledge of construction projects and aid decision-makers for risk identification, risk analysis, and risk response steps in new projects by retrieving the risk-related knowledge of similar previous projects.

Overall, the CBRisk is a web-based platform that can facilitate knowledge-based RM. The tool has a database that represents the corporate risk memory of a particular construction company. The corporate risk memory includes all risk-related knowledge of the previous projects. Once the RM processes are initiated for a new project at the pre-project stage, the CBRisk prepares a template risk register by retrieving the risk-related knowledge of the most similar previous projects. The template risk register prepared by CBRisk includes risks, probability and impact of each risk, and response plans generated for each risk. In this respect, the tool provides holistic and accurate assistance that decision-makers may need at the pre-project stage. During the project, the project team can also monitor the risks and store risk-related knowledge of the current project in the proposed system. This enables the live capture of newly created risk-related knowledge from on-going projects. The tool updates the risk register based on the information provided by the project team. The updated knowledge also becomes available for all employees involved in other projects, enabling inter-project learning. At the post-project stage, the project team makes the final changes on the risk register and it is saved into the database to be used during RM of forthcoming projects. In this respect, the tool enables continuous learning from projects and in-between various projects.

The paper is organized as follows: Section 2 lays the theoretical foundations of knowledge management in construction and the CBR method to develop knowledge-based systems. Section 3 reports the research questions. Section 4 summarizes the findings from a critical review of existing tools, then Section 5 introduces the research gaps identified based on the critical evaluation of the literature. The development process of both the knowledge-based RM process model and the CBRisk tool is elaborated in Section 6, while Section 7 presents the validation of the tool. Finally, conclusions and suggestions for further research are summarized in Section 7.

2. Research Background and Motivation

2.1. Knowledge management in construction

Davenport and Prusak (1998) define knowledge as "a fluid mix of framed experience, values, contextual information, and expert insight". As construction projects have become more complex and challenging in recent years, knowledge has become a critical resource for construction companies. Knowledge as a source of competitive advantage has been widely mentioned in the literature (Eisenhardt & Martin, 2000; Kivrak et al., 2008). To exploit the benefits of knowledge, an appropriate mechanism is needed to capture and disseminate it (Kivrak et al., 2008). Although many efforts have been devoted to the development of effective KM mechanisms in the construction management literature, this research area is not mature and there is still some distance to be covered (Eken, Bilgin, Dikmen, & Birgonul, 2020; Tan et al., 2010). Studies on the development of KM mechanisms to improve RM are even more limited (Dikmen, Birgonul, Tah, & Ozer, 2012; Yildiz et al., 2014). Although it has been widely discussed by researchers that risk-related knowledge of the companies must be embedded in a non-human repository such as routines, databases, or structures (Eken et al., 2020; King, Chung, & Haney, 2008; Öztürk, Arditi, Günaydın, & Yitmen, 2016), construction professionals usually use their subjective judgement for risk-informed decision-making and lack a formalised process for knowledge-based RM.

Some strategies can be implemented to manage knowledge effectively within a company. These strategies can be categorized as "techniques" and "technologies" (Eken et al., 2020). Techniques are defined as non-information Technology (IT) tools while technologies are IT-tools that require the development of a system to manage the knowledge with the help of information technologies (Al-Ghassani, Anumba, Carrillo, & Robinson, 2005). Technologies can provide fertile ground for articulating, storing, and sharing knowledge (Alavi & Denford, 2015; Hayes, 2015). In the construction management literature, several IT-based tools have been developed to systematize KM within construction companies (Arditi, Polat, & Akin, 2010; Eken et al., 2020; Kim & Chi, 2019; Kivrak et al., 2008; Oti, Tah, & Abanda, 2018; Soibelman et al., 2003). However, majority of these tools are generic knowledge management tools, and usually do not offer a special technological solution to support the RM process. As these tools embody all types of knowledge related to construction techniques, stakeholders, suppliers, and RM, it may not be practical to exploit, and re-use risk-related knowledge from the huge database. Consequently, technological solutions specifically developed to support RM should be developed and integrated with the KM system.

2.2. CBR as a technique to develop knowledge-based systems in construction

Rule-based systems, CBR, model-based reasoning, and artificial neural networks (ANN) are techniques that are commonly used to develop knowledge-based systems. The human brain can reach conclusions based on prior information (Goel, Navarrete, Noveck, & Prado, 2017). When faced with a new problem, the human brain retrieves this prior information to find a solution to the current problem. This mechanism of the human brain is the main inspiration of the CBR. CBR, as one of the artificial intelligence techniques, recalls the prior knowledge and experience to provide a starting point for solving the new problem (Zou, Kiviniemi, & Jones, 2017). In other words, it requires knowledge about the problems that emerged in the past and its corresponding outcome/solution.

CBR has been widely preferred in recent years owing to its several advantages over other techniques (Ozorhon, Dikmen, & Birgonul, 2006). One of these advantages is that the reasoning process can be easily followed and it is strengthened by human intervention at several steps, unlike the ANN (Ozorhon et al., 2006). Its high transparency allows the reason for the choice of an outcome to be investigated and analyzed (Yau & Yang, 1998). Furthermore, there are studies that showed that CBR performs better compared to other methods such as ANN (Ayhan & Tokdemir, 2019). Considering that CBR is an analogical learning technique, it has been proved to be a convenient approach to remedy construction problems, which are solved by utilizing experience and experts' knowledge in practice (Ozorhon et al., 2006).

Owing to its above-mentioned benefits, CBR has drawn the attention of many researchers in the project and construction management domain. Bartsch-Spörl et al. (1999) surveyed both the scientific and practical applications of CBR. The study showed that CBR will have promising future, particularly in new areas like self-service and e-commerce applications. Considering the importance of tacit knowledge in the project-based industries, Noh et al. (2000) proposed a cognitive map (CM) to formalize the tacit knowledge and CBR based tool to store and retrieve it. Goh and Chua (2010) utilised a CBR-based approach to construction safety hazard identification. Behbahani et al. (2012) used CBR to develop a knowledge-based system for statistical process control where they developed a new format for representing cases and similarity measures for case retrieval. Hu et al. (2016) conducted a comprehensive literature review of CBR applications in construction management studies considering the articles published between 1996 and 2015. The result of the study indicated that the popularity of CBR applications in construction management literature is increasing due to the similar mind-sets of CBR and problem-solving practices in the construction industry. Most recently, there have been studies on safety risk assessment and management in construction projects such as the work of Preira (2018) and Ayhan and Tokdemir (2019). Zhao et al. (2019) implemented CBR to support green retrofit decisions. Thus, considering its advantages and success of similar applications in the construction management domain, CBR appears as a promising method for knowledge-based risk management.

3. The research questions

The research questions identified at the start of the current study are;

1. What are the features required from a CBR-based tool to support a knowledge-based RM process?
2. Are there any tools proposed in the literature that have the required features? Are there any research gaps?
3. Can CBR be used to develop a tool that effectively supports a knowledge-based RM process?

Findings from a critical literature review and features of the CBR-based tool are discussed in the following sections.

4. Critical review of knowledge-based RM tools and CBR-based models

4.1. Critical review of knowledge-based RM tools developed for construction projects

An extensive review of KM and RM literature revealed that knowledge-based RM tools should be equipped with several critical features to meet the needs of construction practitioners. Firstly, as elaborated above, RM is a systematic process that involves the identification of sources of uncertainty (risk identification), estimating the probability and impact of uncertain events/conditions on a project (risk analysis), generating response strategies, and finally, monitoring the risks (PMI, 2018; J.H.M Tah & Carr, 2001), therefore, an ideal knowledge-based RM tool should support all of these steps to effectively manage the risks of construction projects. Otherwise, the information provided by the tool could be incomplete and impractical to use in engineering practices. Besides, a significant part of the risk-related knowledge in the construction projects is the tacit knowledge which is extremely rooted in individuals' minds and experiences (Eken et al., 2015; Kivrak et al., 2008; Ozorhon, Dikmen, & Birgonul, 2005), therefore a knowledge-based RM tool should be able to capture and formalize the tacit knowledge throughout the whole life cycle of the project. One of the most effective methods for tacit knowledge is live capturing of the risk-related knowledge and storing them in a corporate risk memory. Whereas, in the construction projects, a widely used knowledge capturing method, namely post-project evaluations, can be ineffective for capturing the tacit knowledge as some information might be lost during the project (Ly, Anumba, & Carrillo, 2005). A knowledge-based RM tool should support live risk knowledge capture. In this respect, web-based platforms can be a convenient solution for the development of knowledge-based RM tools, since they enable live knowledge capture without time and location restriction (Aziz, Anumba, Ruikar, Carrillo, & Bouchlaghem, 2006; Han, Kim, Kim, & Jang, 2008; Lam & Ng, 2006). Besides, the employees can access the web-based platforms anywhere in the world, anytime, with any device so that risk-related knowledge can be captured and reused effectively (Han et al., 2008). Another important feature that a knowledge-based RM should have is achieving inter-project learning which refers to the transfer of the knowledge and experience from one project to others, either within the same timeframe or over a period of time (Gieskes & ten Broeke, 2000). Considering that organizations can develop new knowledge by combining and sharing lessons-learned across projects (Kotnour & Kurstedt, 2000), inter-project learning becomes a vital concept for knowledge-based RM. Additionally, knowledge-based RM tools should be equipped with a case retrieval mechanism that can retrieve risk-related knowledge of similar projects. Because similar risks tend to re-occur in similar projects, and the decision-makers can use post-project risk event histories to give more reliable decisions (Dikmen et al., 2008; Okudan & Budayan, 2020). Finally, as Eken et al. (2020) underlined the importance of the quality of the captured knowledge for the reliability of knowledge management systems, a knowledge-based RM system should facilitate collaboration between different parties for capturing knowledge. The same study also stated that the system quality should be maintained by editing, deleting, and modifying the lessons and thus, knowledge-based RM system should also have a mechanism that makes possible it to review and check risk-related knowledge to ensure the reliability of the system. All these features are believed to improve the effectiveness of knowledge-based RM.

As the first step of systematic literature review, critical evaluation of the existing literature was conducted and then research gaps were identified, as also suggested in Jia et al. (2020) and Alizadeh et al. (2020a; 2020b). The critical evaluation of existing knowledge-based RM tools with respect to identified features is presented in Table 1. The tools depicted in Table 1 are all aimed at facilitating knowledge-based RM for project management and listed in ascending order of their publication years.

Table 1. Critical evaluation of the knowledge-based RM tools

Reference	**Brief description**	**Pros**	**Cons**					
			A	**B**	**C**	**D**	**E**	**F**
Tah and Carr (2001)	The first software prototype that can facilitate knowledge-based RM	• Supports a knowledge-based RM process • Introduces a common language for describing risks and remedial measures.		X	X	X	X	X
Zoysa and Russell (2003)	A knowledge-based risk identification system in large infrastructure projects	• Capable of improving responsiveness of existing knowledge-based approaches to project attributes		X	X	X	X	X
Choi et al. (2004)	A risk analysis software that is built upon an uncertainty model based on fuzzy concept	• Capable of considering the degree of uncertainties involved in both probabilistic parameter estimates and subjective judgements		X	X	X	X	X
Han et al. (2008)	A web-based decision support system for RM that can satisfy the specific needs of the construction practitioners	• Supports project managers in key areas such as bid decision, profit prediction etc. • Has web-based architecture which eases the accessibility	X	X		X	X	X
Dikmen et al. (2008)	A computer-based RM tool that can facilitate knowledge-based RM	• Capable of establishing lessons learned database and facilitating risk assessment throughout the project's life cycle		X	X	X	X	
Tserng et al. (2009)	An ontology-based risk management framework to enhance the RM performance by improving the RM workflow and knowledge reuse	• Capable of facilitating the identification, analysis, and response of project risks		X	X	X	X	X
Cardenas et al. (2013)	An approach to capture and integrate risk-related knowledge to support RM of construction projects	• Capable of identifying top risks in tunnel works	X	X	X	X	X	X
Serpella et al. (2014)	A methodology based on a three-fold arrangement that includes modelling of the risk management function, its evaluation, and the availability of a best practices model	• Allows clients and contractors to develop a project's risk management function based on best practices	X	X	X	X	X	X
Yildiz et al. (2014)	A knowledge-based risk mapping tool for systematically assessing risk-related variables	• Supports decision-making at the bidding and contingency estimation phase	X	X	X	X	X	X

		• Introduces a novel methodology to estimate potential risk paths based on previous projects' knowledge						
Ding et al. (2016)	An ontology-based tool for construction risk knowledge management in BIM environment	• Capable of linking the applicable knowledge to the specific objects in the BIM	X	X	X	X	X	X

Note: **A:** The tool does not support all RM processes; **B:** The tool cannot facilitate live knowledge capture, **C:** The tool is not established on a web-based platform; **D:** The tool is not equipped with a systematic case retrieval mechanism; **E:** The tool does not support inter-project learning, **F:** The tool does not check the reliability of lessons learned.

Consequently, focus on risk assessment rather than all RM processes, lack of systematic case retrieval mechanism and live knowledge capture, no support for inter-project learning and review/checking of lessons learned are the main limitations of the existing studies depicted in Table 1. Moreover, most of the tools do not operate on a web-based platform.

4.2. Critical review of CBR-based RM support tools and models

As also mentioned in Section 2.2, CBR depends on the "case" which is a conceptualized piece of knowledge representing an experience. CBR is a cyclic process that consists of 4 steps. These steps are Retrieve, Reuse, Revise, and Retain (Aamodt & Plaza, 1994). These steps are also known as 'the four REs' (Zou et al., 2017). Retrieve, which is a process of searching and determining the most similar and relevant case or cases (Aamodt & Plaza, 1994; Lopez De Mantaras et al., 2005), is seen as core and the most important step in any CBR systems (Lu et al., 2013). Since the database is expected to include a large number of risk-related knowledge of construction projects, the performance of case retrieval is strongly correlated with the quality and accuracy of retrieved cases (Zou et al., 2017). Additionally, as elaborated above, CBR provides a starting point for the new problem. Thus, the system, which fails to retrieve the most relevant case, cannot provide an appropriate starting point for solving the new problem (Castro, Navarro, Sánchez, & Zurita, 2009). In this respect, case-retrieval has an indispensable role within the CBR cycle. Although the retrieve is seen as the core of CBR, it is undeniable fact that all steps must be considered to develop a reliable and robust CBR system. For instance, "Retain" step is also crucial for the continuity of the system since it dictates to store new experiences in the database. Otherwise, the developed system will not capture up to date knowledge, and eventually, cases in the database will be out of date. Thus, the CBR system must embody all the steps from Retrieve to Retain.

The accuracy of case retrieval relies on the comprehensiveness of case representation and the accuracy of the similarity measurement method. The case representation is the process of representing the case by using features (attributes). To retrieve the most similar historical cases, firstly, cases should be represented in a way that makes it possible to reflect all dimensions of the cases. Using insufficient and/or inappropriate features lead to failure of the whole retrieval process since the similarity between the projects is measured based on the similarity between the project features (Fan, Li, Wang, & Liu, 2014). Using a sufficient number of project features is, therefore, key for accuracy. Formats of the project features are also critical for a well-designed case retrieval step. These formats are usually crisp symbols, crisp numbers, fuzzy linguistic variables (Castro et al., 2009; Faez, Ghodsypour, & O'Brien, 2009; Liao, Zhang, & Mount, 1998). Although most of the studies are conducted by considering just crisp symbols and crisp values, it is not controversial to assert that the CBR system greatly benefits from the use of fuzzy linguistic variables since it is hard to represent all critical areas of the construction projects by using just crisp numbers and crisp symbols (Fan et al., 2014; Liao et al., 1998). Consequently, a similarity measurement method, which can consider all formats of features including fuzzy linguistic variables, must be integrated into the case-retrieval.

For measuring the similarity between the cases, different similarity measurement methods have been proposed in the literature, however, the vast majority of these similarity measurement methods such as Castro et al. (2009) and Kong et al. (2013) consider only crisp numbers and crisp symbols, which, in turn, cause abovementioned drawbacks. However, Fan et al. (2014) developed a hybrid similarity measurement method that can improve the accuracy of case retrieval. This new method brings great flexibility to case representation. Owing to its ability to use fuzzy linguistic variables, cases in CBR systems could be represented in detail so that it outperforms the other similarity measurement methods with unprecedented accuracy.

The literature review presented above revealed that cyclic CBR processes, hybrid similarity measurement including fuzzy linguistic project features, a comprehensive definition of project features are the critical features to design effective and efficient CBR-based systems. Thus, in Table 2, the existing studies of knowledge-based RM tools/methods using CBR were reviewed with respect to these features.

Table 2. Critical evaluation of previous CBR tools and models developed to support RM

Reference	**Brief description**	**Pros**	**Cons**		
			A	**B**	**C**

Kumar and Viswanadham (2007)	Developed a CBR-based decision support system framework for construction supply chain RM	• Capable of providing feasible solution based on retrieved cases	X	X	X
Liu et al (2009)	Proposed CBR approach for assessment of BOT projects' risks	• The system can assess the impact of the risks by retrieving similar cases	X	X	X
Forbes et al. (2010)	Developed a tool that can suggest the most convenient RM technique	• Capable of identifying the most convenient RM technique with 90% accuracy • Demonstrated the applicability of CBR to RM	X	X	X
Lu et al. (2013)	Developed a CBR-based tool for safety risk analysis for subway operation.	• Developed an effective CBR system that can analyze safety risk. • Proposed a method that increases the applicability of CBR to various real-world settings.	X	X	X
Fan et al. (2015)	Demonstrated the applicability of CBR to RM and employed CBR to generate risk response strategies.	• Capable of generating risk response strategies for the subway projects • Proved that CBR can support project manager to make a better risk-informed decision	X	X	X
Zou et al. (2017)	Developed a case retrieval method for construction projects risk management based on Natural Language Processing.	• Capable of case retrieval combining Natural Language Processing and Vector Space Model	X	X	X
Yu et al. (2018)	Developed a computer-based CBR system that can generate risk responses for the urban water supply network during a natural disaster.	• Capable of generating response strategies to risks connected with urban water supply network • Capable of supporting emergency decision-making	X	X	X
Somi et al. (2020)	Proposed a CBR-based framework to identify risks of renewable energy projects	• Proposed framework improves the accuracy of risk identification in renewable energy projects.	X	X	X

Note: **A:** The tool/method does not embrace a cyclic CBR process; **B:** The tool/method does not employ fuzzy linguistic variables; **C:** The tool/method does not use a list of comprehensive project features.

5. Research Gaps Based on the Critical Evaluation of the Literature

Followed by the critical evaluation of the literature, research gaps in the existing literature about knowledge-based RM tools have been identified and summarized as follows:

1. Although there are tools (such as Yildiz et al., (2014)) proposed in the literature that store lessons learned to enable learning from previous projects, none of the existing knowledge-based RM tools has an effective case retrieval mechanism to select the most similar cases, thus, this is identified as the first research gap. Although risk-related

knowledge obtained from similar previous projects is valuable input, without an effective retrieval mechanism, it is hard for decision-makers to determine which past projects are similar to a current project. Thus, it was hypothesized that a knowledge-based RM should be developed with a systematic case-retrieval mechanism to exploit the risk-related knowledge of similar projects.

2. To exploit a knowledge-based RM tool effectively, the knowledge that emerged in projects should be captured throughout the projects. However, most of the existing studies rely on a standalone and intranet architecture and fail to capture live risk-related knowledge. Besides, all the knowledge captured throughout the projects should be checked by the central risk management department in terms of its reliability and reusability to avoid unnecessary or erroneous knowledge in the system. Consequently, it was hypothesized that a web-based structure enabling live knowledge capture and checking is of paramount importance for a knowledge-based RM tool.
3. The majority of the existing studies focus on just one step of the RM such as risk identification or risk assessment. However, RM is a cyclic process, and all steps are interrelated with each other, in other words, the success of one step depends on the inputs obtained from other steps of RM. Therefore, a system that integrates all steps of RM can be important for the success of RM. Consequently, a knowledge-based RM tool that integrates all steps of RM was aimed to be developed.
4. Although CBR is a cyclic process that consists of 4 steps, most of the existing studies focus on just one step of CBR, namely the case retrieval step, as shown in Table 2. However, a system based on a CBR can only be exploited effectively by developing a system that includes all steps of CBR, which is identified as one of the features of the proposed tool.
5. Another research gap is that existing case retrieval mechanisms usually depend on similarity assessment based on crisp numbers and involve a limited number of project features, leading to problems in finding similar projects. Thus, it was hypothesized that a comprehensive list of fuzzy linguistic project features should be identified for a more effective case retrieval process.
6. Literature findings reveal that most of the CBR-based RM tools/methods are applicable to a single project type such as subway projects or building projects. However, it limits the usability of the tool in practice since construction companies usually perform various

types of construction projects within their portfolio and learning from different project types is also possible. Thus, it was hypothesized that a knowledge-based RM tool that supports all project types would be useful.

In this respect, based on literature findings and research gaps, the main objective of this study is to develop a knowledge-based RM process model and a web-based tool considering all of the above-mentioned requirements to successfully implement this process model.

6. Research Methodology

The research methodology utilized in this study is shown in Figure 1. Initially, a comprehensive literature review was conducted to get a deep insight into KM and RM and tools to integrate them. Previous efforts were then analyzed to identify the requirements for knowledge-based RM and identify the possible research gaps. Consequently, based on the research gaps, the requirements for a new tool, namely CBRisk and its features were determined by the research team. Then the tool was developed in light of these features and requirements. The web-based tool works in Apache Web Server and uses the PostgreSQL database. After developing the tool, black-box testing methods were used to test the functionality and integrity of the software. Later, the validation of the tool and process model was performed through expert review meetings, which was vital to ensure that the tool meets the needs of practitioners.

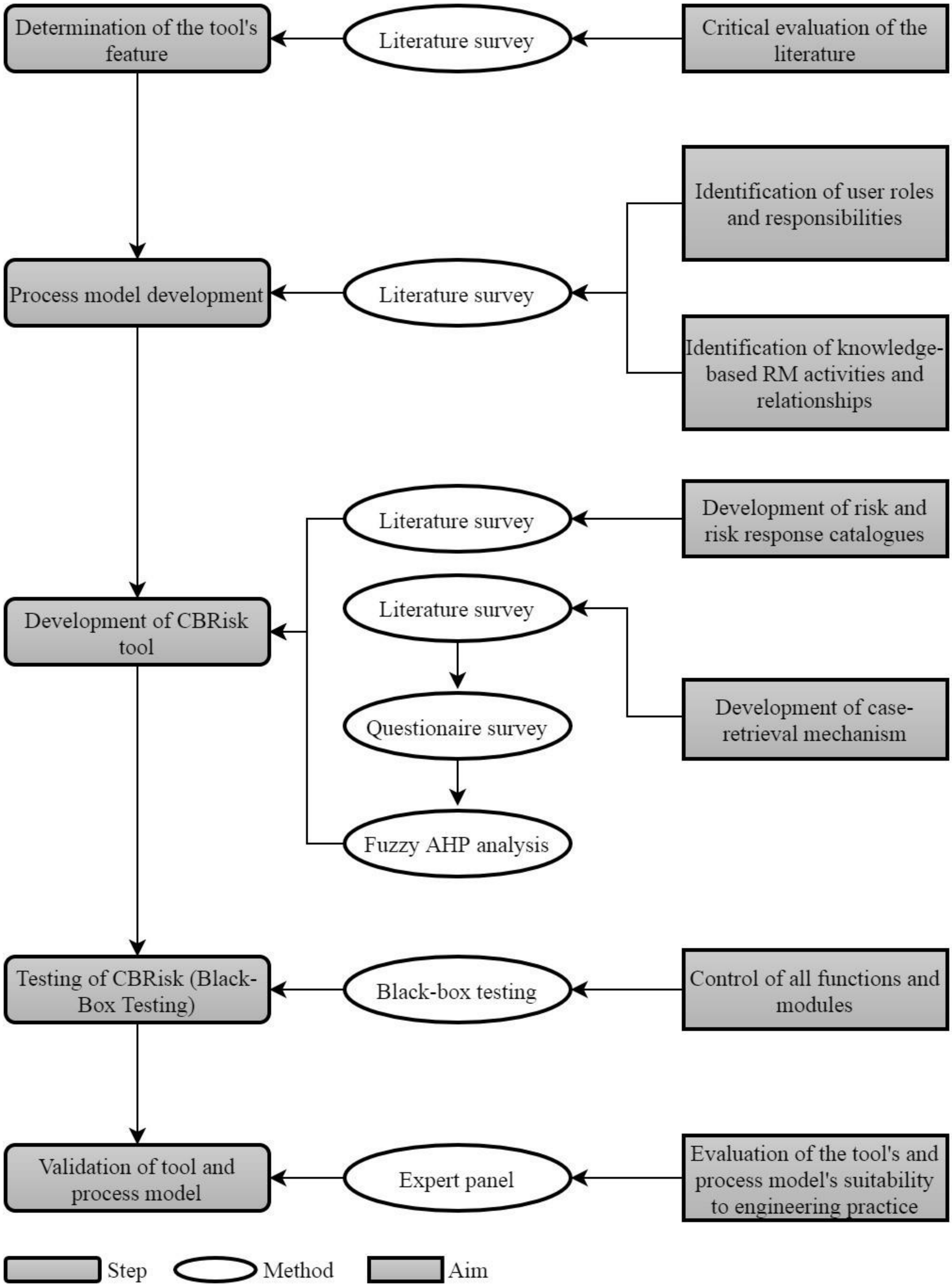


Figure 1. Research Methodology

6.1. Software architecture

6.1.1. Overview of the tool

The CBRisk tool was designed and developed in-house as a web-based application to ease it is accessibility. The tool is hosted in the Apache server and coded by using the Phyton programming language. Since open-source products were used such as Apache and Phyton, the system development and operation costs were minimized, in turn, reliability of the system was further increased. Additionally, a PostgreSQL database was used to store all data of the tool. Thanks to its versatile structure, the tool can be accessed via all web-browsers and mobile devices. The tool does not require additional software installation so that companies will not have to pay license fees for any other software.

The knowledge-based RM structure was designed as shown in Figure 2. The CBRisk tool lies at the core of this system. It provides various interfaces for various tasks that are vital for performing effective RM. As depicted in Figure 2, the tool has its database which can also be named as corporate risk memory and this database includes risk-related knowledge about past projects. This risk-related knowledge consists of project features (project ID, project features, etc.) and risks of each project, impact and response plan of each risk, and finally information showing the effectiveness of the response plan. Owing to its web-based structure, the system is accessible anywhere in the world, anytime, with any device. Besides, the tool does not have high system requirements so that companies do not have to cope with the challenges of huge technological investments. Given the fact that huge investments and license fees are one of the main disadvantages of existing organizational learning tools (Ozorhon et al., 2005), the relatively low technological investment required for the tool can be identified as an advantage.

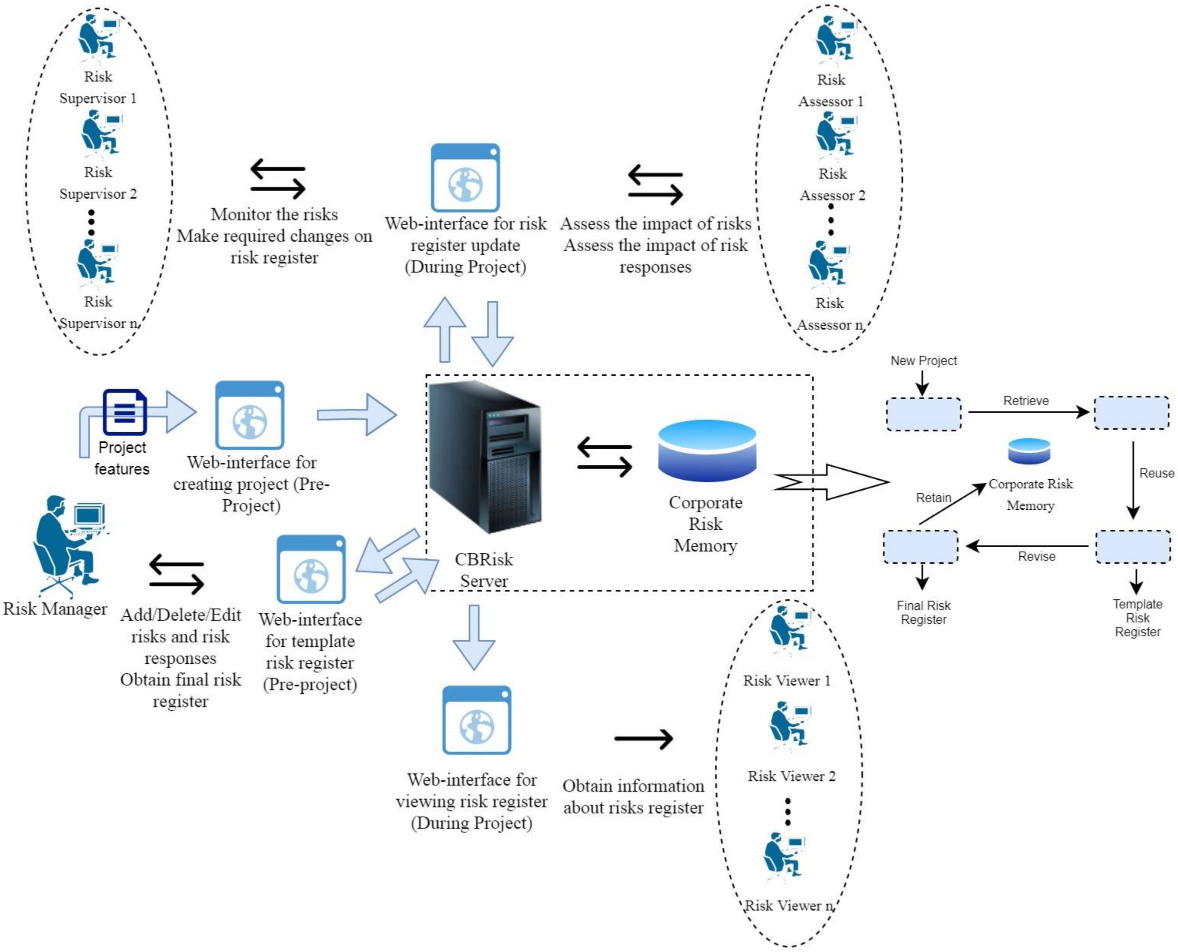


Figure 2. Structure of knowledge-based RM

6.1.2. Knowledge-based RM activities throughout project life cycle

Figure 3 is the process model and shows the knowledge-based RM activities to be performed with the aid of the tool. As stated above, this tool embraces all RM processes and aids the project team from the pre-project stage to the post-project stage. The first process of the RM is the identification of the risks at the pre-project stage. Accurate and comprehensible risk identification is a crucial process of RM (Wang, Dulaimi, & Aguria, 2004). Because subsequent processes are constructed upon the identified risks. Additionally, risk identification is critical for the bidding phase since unpredicted risks can increase the cost and duration of the project enormously. The tool offers an innovative and systematic solution to risk identification. As shown in Figure 3, the CBR system starts working in the background after the new project is created by inserting its specific features such as duration, project value, etc. Then, the CBR system retrieves the most similar projects from the database and merges risks of these similar past projects. Given the fact that similar risks tend to re-occur in similar projects, these risks are expected to occur in this new project. Decision-makers were also assisted during the risk analysis process. The tool calculates the probability and impact of each risk identified in the previous process by following the methodology as explained in Section 3.3. The third RM management process performed at the pre-project stage is generating a response plan for each risk. The tool also guides decision-makers when it comes to generating a response plan to each risk. The tool lists previously performed risk responses and, their impact on time and cost from the previous projects for each risk. Thus, decision-makers can display which responses were taken against each risk in these similar past projects. Since the system retrieves response plans of only similar project’s risks, these responses could also be implemented in this new project. In short, the software provides a template risk register based on similar past projects stored in the database.

It is useful to draw attention to the fact that although similar risks tend to re-occur in similar projects, there could be still differences between each project in terms of RM. Some projects might possess unprecedented challenges that have never been coped with so that template risk register provided based on past projects could be somewhat insufficient. The tool provides a solution to this issue. The decision-makers can modify the template risk register to ensure that the final risk register prepared at the pre-project stage fits the new project. To ease this modification, the tool provides a risk and risk response catalogue. The risk catalogue consists of all possible risk items, while the risk response catalogue includes possible response actions that can be used to mitigate and eliminate the risks in a project. The risk catalogue is formed according to the risk breakdown structure (RBS) code which consists of risk ID, risk name, description, responsibilities. The catalogue consists of 63 pre-defined risks and developed by considering Tah and Carr (2001), Zhi (1995), and Dikmen et al. (2008). The structure of the risk catalogue is demonstrated in Table 3. The risk response catalogue consists of risk response strategy and action. Mainly 4 response strategies were determined based on PMBOK (2018). These are accept, transfer, mitigation, and avoid. The response catalogue includes 30 default response actions which were determined based on literature review and brainstorming. However, these catalogues could be further modified and improved by an authorized user if necessary.

Table 3. The structure of risk catalogue (an example)

Risk Type	Risk Category	Risk
Country	Political Environment	War
		Revolution
		Civil Disorders
		Change in governmental policies
Construction Industry	Law and regulations	Incompatible arbitration system
		Complex planning approval and permit procedures
		Import/export restrictions
		Constraints on employment availabilities
		Constraints on materials availabilities
		Monetary restrictions
Project	Construction equipment	Low productivity
		Breakdown
		Late delivery

The monitoring process is performed to monitor the implementation of risk response plans, track identified risks, and identify new risks emerging during the project (PMI, 2018). The effectiveness of the risk responses is also inserted into the system periodically in this process. Monitoring the risks and generating risk responses for new risks have a cyclic relationship (Dikmen et al., 2008). During the project, the team identifies new risks and generate responses to them. Then, the risk register is updated accordingly. As depicted in Figure 3, final changes should be made at the post-project stage. In this phase, the actual impact values associated with risk events, risk impact values, and effectiveness of the risk responses are saved into the system. This phase is critical since the final risk register is saved to the database and used in the RM of forthcoming projects. Thus, the reliability of the final risk register is key for the reliability of the system. In this respect, this tool uses the principles of machine learning since it continuously learns from new projects.

6.1.3. User roles and responsibilities

The quality of the knowledge captured and saved in the database is a crucial factor for the reliability of the tool. Because the CBR uses its database to identify risks, risk responses, etc. Each irrelevant knowledge saved into the database can potentially affect the reliability of the system. Thus, different types of roles and responsibilities are required to implement the structure as given in Figure 2. Authorities such as creating projects, adding/deleting risks and risk-related knowledge cannot be granted to every user since changes are done by incompetent and irresponsible users may put system reliability at risk (Eken et al., 2020). To eliminate any useless and unreliable data and maximize the effectiveness of the tool, several user roles with varying degrees of responsibilities were developed as shown in Figure 4. These roles were determined by deeply examining the existing studies (Dikmen et al., 2008; Eken et al., 2020). As depicted in Figure 4, four user roles were proposed as “risk manager”, “risk supervisor”, “risk assessor” and, “risk viewer”. Each of them was granted with different authorities so that uncontrolled intervention to the system was further avoided. The risk manager has the main responsibility. The authority of creating, modifying, and deleting the projects in the system is granted to this role. In order words, the risk manager initiates the RM processes by creating the project. The risk manager’s other task is to create a template and final risk register at the pre-project stage. All risk and risk response catalogues as well as country risk ratings are inherited only by the risk manager. An employee working as a bid and tender specialist in the head office can be assigned to this role since risk identification and generating risk response plans are mainly needed during the bid preparation. Lastly, the risk manager decides which employees from each project are assigned to other roles such as risk assessors and risk viewers. “Risk supervisor” is responsible for monitoring risks during the project stage. In other words, this role is responsible for recording the risk event that happened throughout the project and updating the risk register accordingly. Additionally, generating risk responses for the new risk events during the project stage is under the responsibility of the “risk supervisor”. The tool provides a risk response catalogue to carry out this task. This role can be assigned to the project manager or planning manager who works on the project site so that the risks could be monitored closely. “Risk assessor” assesses the impact of the risk and effectiveness of the risk responses by using the project’s documentation. While impacts of the risks are evaluated based on the 5-point Likert scale, the effectiveness of the risk responses is measured based on the impact on time and cost. To carry out this task, the “risk assessor” collects all the means of tangible and intangible information (Dikmen et al., 2008). It is believed that the cost control engineer who works in the project site fits this role since he/she can access to cost-related documents of the project. Both “risk supervisor” and “risk assessor” update the risk register in the light of the knowledge that they captured. Namely, they capture the risk-related knowledge. Thus, their collaboration is vital to rigorously capture risk-related knowledge of each project.

During the risk identification process at the pre-project stage, a responsible party or department was assigned to each risk. The responsibility of these employees is to manage risks and implement risk responses identified previously by the "risk manager" or "risk supervisor". These employees need to access risk-related information so that they can learn their responsibility and make the required contribution to the RM. Thus, the "risk viewer" role was created. This role is privileged to access the system; however, they cannot make any changes. They can only search and view risk-related information on the project to learn their responsibility. At the post-project stage, as shown in Figure 3, the risk manager, risk supervisor and the risk assessor decide on final risks, risk impact values, risk responses, and their effectiveness. Simply, all RM team collaborates to discuss all inserted risk-related knowledge. These meetings are believed to improve the overall reliability of the data inserted into the system. After all, the team is agreed on the risk register, the project is terminated, and the risk register is saved to the database to be used in forthcoming projects.

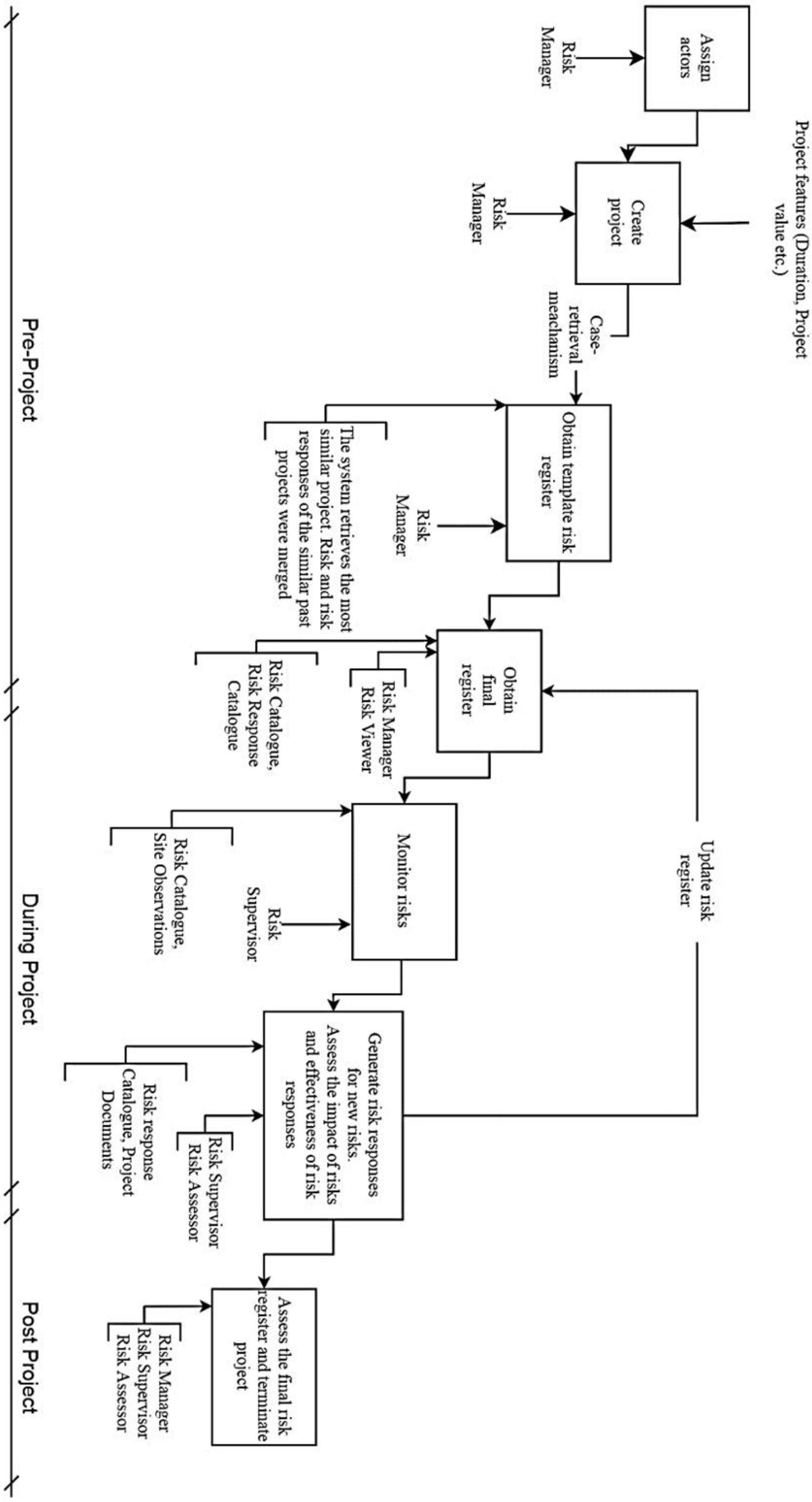


Figure 3. Process Model

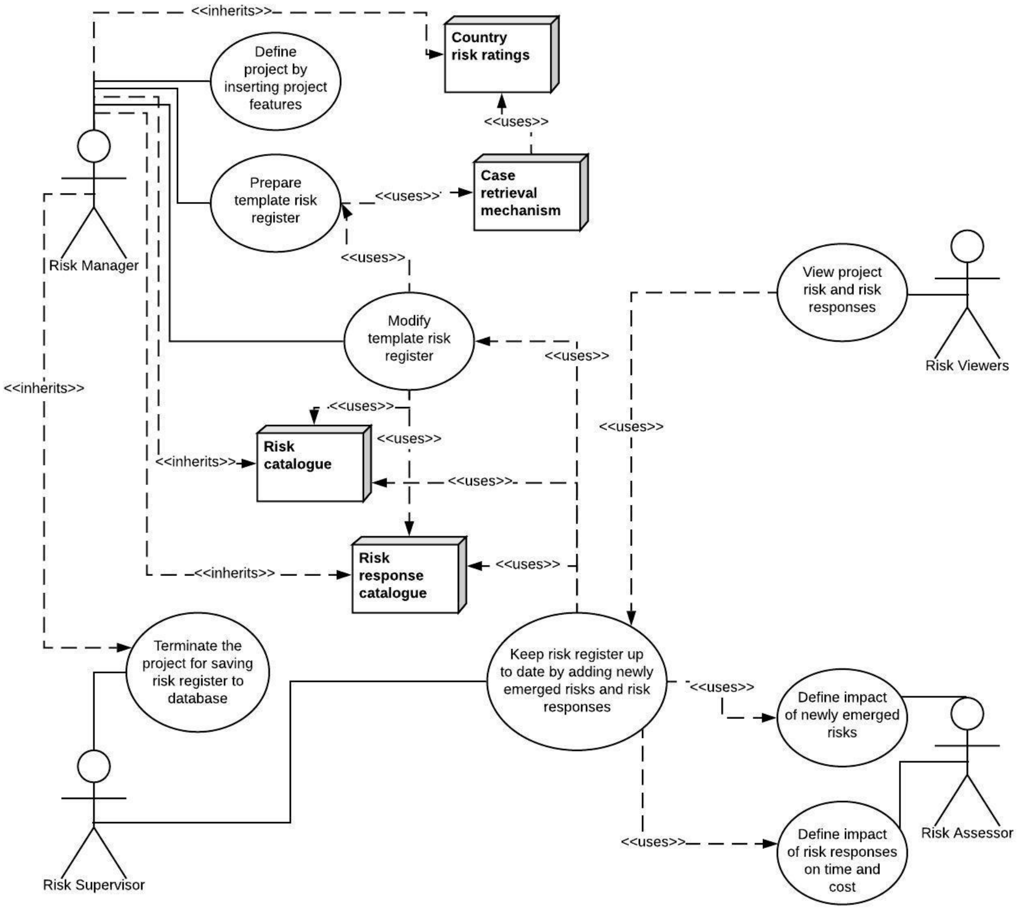


Figure 4. Use case diagram

There are primarily two workflows within the system. The first one is creating a risk register at the pre-project stage. This risk register is indispensable to calculate risk-adjusted cost and duration so that potential cost and time overruns could be avoided (Dikmen et al., 2012). The detailed procedure for this task is presented in Figure 5. Firstly, the project has to be created to initiate the process. "Risk manager" has to enter various features related to a project that he/she wants to create. These features are shown in Table 4 and they are employed to measure the similarity between the current project and each project stored in the database. Determination of project features and their normalized weights in Table 4 are elaborated at Sections 4.2.1 and 4.2.2, respectively. After the project is created, the tool retrieves the most similar projects from the database. Then, the tool combines the risks of these similar projects with their response information, probabilities, and impacts. Finally, the template risk register is created and displayed by the tool. The "risk manager" could modify the register in case of need. A risk and response catalogue could be used during this modification. As shown in Figure 6, the second workflow is monitoring the risks and updating the risk register in the light of captured risk-related knowledge. Knowledge capture is the responsibility of both "risk supervisor" and "risk assessor". The actual risk impact values, the effectiveness of risk response plans, new risks that emerged during the project are continuously monitored, calculated, and entered the system. The CBR risk tool also displays information about project risks. In this respect, the system could be used to get information about project risks and risk responses.

Table 4. Project features and their normalized weights (adopted from Ling et al. (2004), Han et al. (2007), Eybpoosh et al. (2011), Fidan et al. (2011), Nguyen et al. (2015) and Eken et al. (2020))

Main Features	Normalized Weights of Criteria	Sub-criteria	Formats of the features	Normalized Weights of the Sub-criteria
Project type	0.0741	-	CS	-
Country	0.0873	-	CN	-
Delivery system	0.0751	-	CS	-
Project value	0.0929	-	CN	-
Duration	0.0727	-	CN	-
Total	0.0632	-	CN	-
Contract type	0.0962	-	CS	-
Design-related features	0.0620	The complexity of the design	Fuzzy LV	0.16
		The completion level of	Fuzzy LV	0.25
		Constructability level	Fuzzy LV	0.31
		Quality of design	Fuzzy LV	0.29
Construction-related features	0.0917	The complexity of construction methods	Fuzzy LV	0.51
		Accessibility of the site	Fuzzy LV	0.49
External conditions-related features	0.0891	The comprehensiveness of geotechnical investigation	Fuzzy LV	0.77
		Climate & weather conditions	Fuzzy LV	0.23
Project management-related features	0.0899	The strictness of quality management requirements	Fuzzy LV	0.27
		The strictness of environmental management	Fuzzy LV	0.21
		The strictness of safety management requirements	Fuzzy LV	0.24
		The strictness of project management requirements	Fuzzy LV	0.28
Contract-related features	0.1058	Vagueness in contract clauses	Fuzzy LV	0.66
		Clarity of contract documents	Fuzzy LV	0.34

Note: CS, CN, and Fuzzy LV represent a crisp symbol, crisp number, and fuzzy

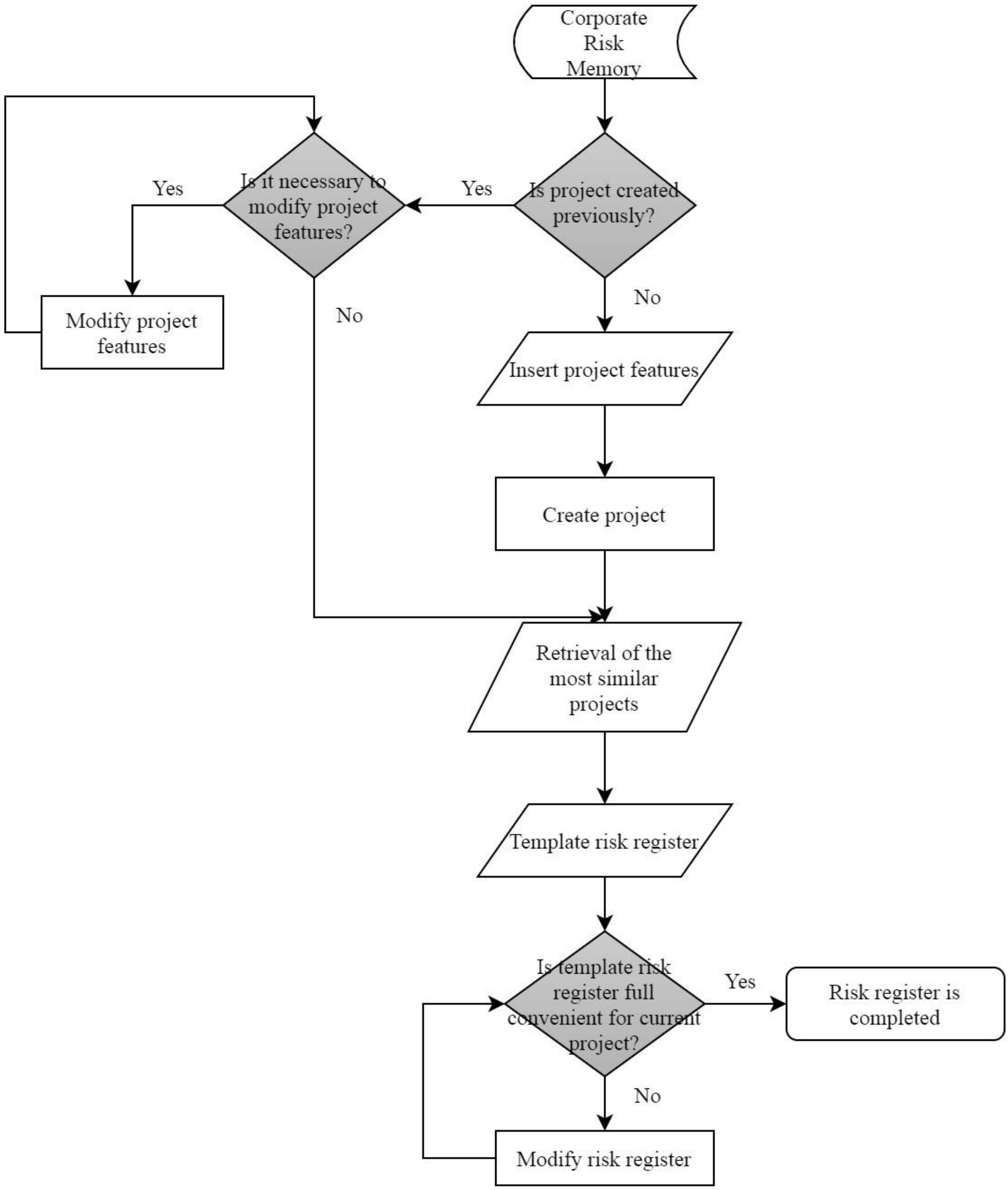


Figure 5. Flowchart for creating risk register at the pre-project stage

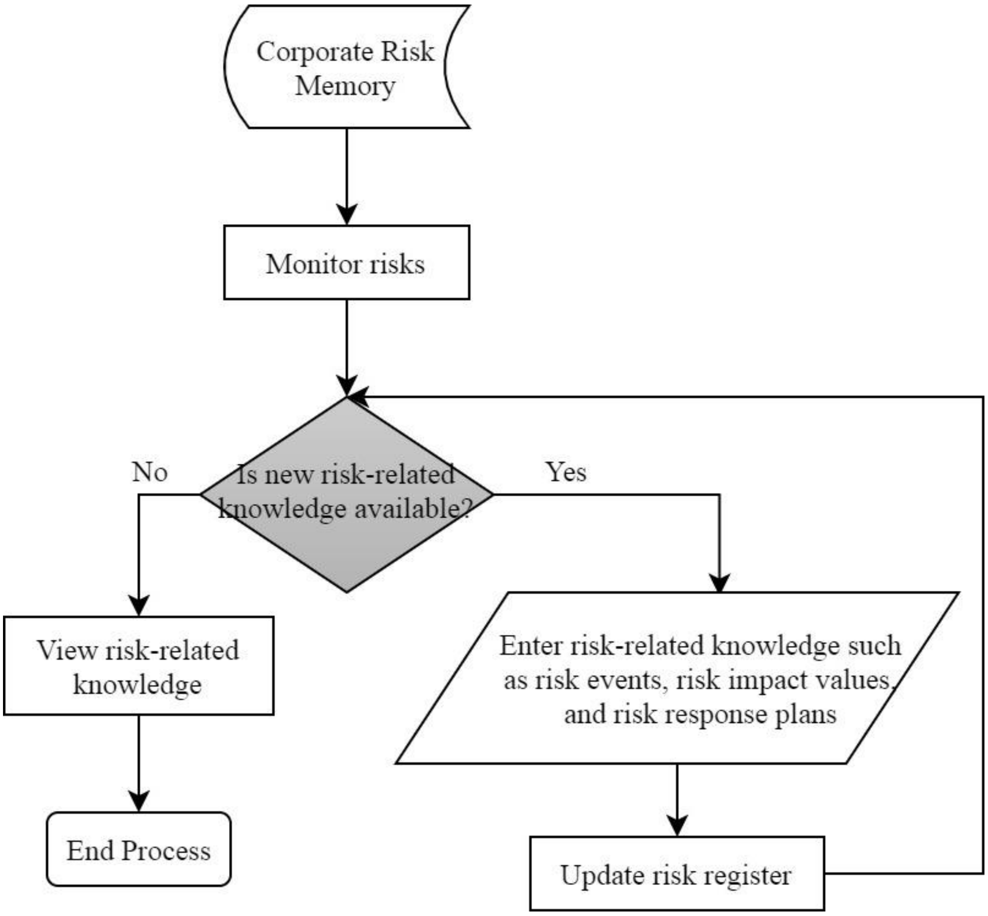


Figure 6. Flowchart for risk monitor process

6.2.Development of case retrieval mechanism

Case retrieval is the process of searching and determining the most similar case or cases (Aamodt & Plaza, 1994; Lopez De Mantaras et al., 2005). Similarity methods are used to carry out this process. In this study, the hybrid similarity measurement proposed by Fan et al. (2014) was used. The rationale behind this is that this method can employ diverse formats of the project features such as fuzzy linguistic variables so that all critical areas of the projects are represented. After the specific project features were determined to represent construction projects, this similarity method necessitates determining the weights of each project feature since some of them could be more important than the others. Thus, the fuzzy AHP method was used to determine the weights in this study.

6.2.1. Determination of project features

The accurate case retrieval mechanism is regarded as a catalyst for the performance of CBR systems (Zhang & El-Gohary, 2013). The use of insufficient and/or inappropriate features leads to failure of the whole retrieval process since the similarity between the projects is measured based on the similarity between the project features (Fan et al., 2014). Several factors affect the performance of case-retrieval. The first one is the comprehensiveness of the features that are used to represent projects. Few project features fail to represent all critical areas of complex construction projects, therefore similarity between the projects can be miscalculated. Using a sufficient number of project features is, therefore, key for accuracy. Besides the comprehensiveness of the project features, the second factor is the format of the project features. As elaborated many times, the use of fuzzy linguistic project features can bolster the performance of case retrieval. The use of only crisp numbers and crisp symbols often becomes insufficient. Utmost attention was therefore paid to determine project features. An extensive literature review was conducted to extract as many project characteristics as possible. Consequently, 12 main project features and 14 sub-project features were identified based on studies such as Ling et al. (2004), Han et al. (2007), Eybpoosh et al. (2011), Fidan et al. (2011), Nguyen et al. (2015), Eken et al. (2020). The features used in the case retrieval mechanism are shown in Table 4.

Although the country project feature was stated as one of the important features in the literature, studies such as Eken et al. (2020) measure the similarity between historical and target cases based on the name of the countries. In other words, if the projects are placed in the same country, the similarity between these projects is assigned as one, otherwise, the similarity is zero. However, these countries may have much more in common, and similarity between them cannot be measured based on their names. Therefore, in this study, the similarity between countries is calculated based on their risk ratings which are crisp numbers. Thus, the accuracy of the system was improved. There are different organizations providing information about the risk ratings for the countries, however, in this study, the risk rating database is prepared by using Credendo (2019). Country risk ratings change over time and/or company experience in each country may indicate a different risk rating for the country. Thus, the risk manager can modify these ratings within the tool.

6.2.2. Determination of weights

Hybrid similarity measurement requires the weights of each project feature. A questionnaire was prepared for determining the hybrid similarity measurements. Then, a fuzzy AHP analysis was performed on the survey data. The prepared questionnaire consisted of three parts. The first part included questions about respondents and their companies. This part was crucial to ensure that their competency is at the desired level for this study. In the second and third part, respondents were asked to complete pairwise comparisons of 12 main project features and 14 sub-project features, respectively.

In this study, 15 experts were selected by using judgment sampling based on their backgrounds, and the demographics of these experts are shown in Table 5. The appropriateness of this sample size was also evaluated for performing the fuzzy AHP. In the literature, single and strict rules are not proposed for the sample size of AHP surveys (Thomas L Saaty & Özdemir, 2014). However, many studies pinpointed that AHP is capable of providing reliable results with a small sample size (Wong & Li, 2008). In this respect, AHP is distinguished from descriptive techniques that require laypeople rather than an expert panel (Cevikbas & Koksal, 2018). By contrast, the large sample size may lead to unreliability due to the *cold-called* respondents (Cheng & Li, 2002). Thus, it should be clearly stated that AHP necessitates quality data rather than a high quantity of data (Gurgun & Koc, 2020). As seen in Table 5, the experts are highly experienced in risk management and international construction projects so that their experience could be considered global experience that can be utilized elsewhere in the world (Budayan, Okudan, & Dikmen, 2020). Besides, to improve the reliability of the survey, the data was collected through face-to-face interviews (Çevikbaş & Köksal, 2019). In this way, all respondents were well informed about the survey, all the misunderstandings could be avoided. Last but not least, consistency is another factor affecting the reliability of the survey. However, fuzzy AHP eliminates this issue since it is capable of calculating the consistency of pairwise comparison matrices. Saaty (1980) pointed out that the answers of the participants are considered inconsistent when overall consistency is greater than 10%. Then, these answers cannot be taken into consideration.

Table 5. Demographics of the Respondents

Sample Specifications	Counts and Percentages		
Parent organization	Client	Main Contractor	Sub-contractor
	4 (%26.66)	10 (%66.66)	1 (%6.66)

<table>
<tr><td rowspan="2">Size of the organization</td><td colspan="2">Small</td><td>Medium</td><td>Large</td></tr>
<tr><td colspan="2">2 (%13.33)</td><td>3 (%20)</td><td>10 (%66.66)</td></tr>
<tr><td rowspan="2">Experience of the organization in International</td><td colspan="2">0-20</td><td>20-50</td><td>50-100</td></tr>
<tr><td colspan="2">8(%53.33)</td><td>4(%26.66)</td><td>3(%20)</td></tr>
<tr><td rowspan="2">Experience of the organization</td><td colspan="2">0-20</td><td>20-50</td><td>50-100</td></tr>
<tr><td colspan="2">4(%26.66)</td><td>5(%33.33)</td><td>6(%40)</td></tr>
<tr><td rowspan="2">Experience of the respondent</td><td colspan="2">0-10</td><td>10-15</td><td>15-30</td></tr>
<tr><td colspan="2">4(%26.66)</td><td>7(%46.66)</td><td>4(%26.66)</td></tr>
<tr><td rowspan="2">Experience of the respondent in risk management</td><td colspan="2">0-5</td><td>5-10</td><td>10-25</td></tr>
<tr><td colspan="2">5(%33.33)</td><td>3(%20)</td><td>7(%46.66)</td></tr>
<tr><td rowspan="2">Education level</td><td colspan="2">BSc.</td><td>MSc.</td><td>PhD.</td></tr>
<tr><td colspan="2">3(%20)</td><td>9(%60)</td><td>3(%20)</td></tr>
<tr><td rowspan="2">Role of the respondent</td><td>Coordinator/Ceo</td><td>Planning Specialist</td><td>Tendering Specialist</td><td>Academician</td></tr>
<tr><td>6(%40)</td><td>3(%20)</td><td>3(%20)</td><td>3 (%20)</td></tr>
</table>

A Matlab script has been developed to perform fuzzy AHP analysis and the output of this analysis was integrated into the case-retrieval mechanism of the CBRisk tool. To avoid any coding errors, the computational accuracy was tested using the data presented by Okudan and Budayan (2020). The test results verified that script provides correct results. The script was further strengthened with the consistency check feature. The consistency ratios of the matrices were 0.0077, 0.0076, and 0.0071. Thus, they were found consistent. Consequently, the weights of the project features were determined at the end of the fuzzy AHP analysis were presented in Table 4.

6.2.3. Hybrid similarity measurement method

The term “historical case” refers to construction projects stored in the database while a new construction project is called as a target case. The similarity is calculated between the target case and each historical case. To measure the similarity between the two projects, first local similarities are found by measuring the similarity of each feature. Then, these local similarities are aggregated to calculate global similarity by using the weights in Table 4. Three different formats of project features were used. These are the crisp symbol, crisp number, and fuzzy linguistic variables. The formulation for each format is as follows:

1) Values of the crisp symbols are kind of enumeration values so that there are no quantitative relationships among these features. A comparison of these values cannot be made. For instance, airports and railways are among the example of “project type”. These are categorical values and cannot be compared mathematically. Thus, the

following formula is used to calculate similarity. In Eq. (1), $Sim_j(Z_0, Z_i)$ denotes similarity between the historical case Z_i and target case Z_0 concerning feature C_j.

$$Sim_j(Z_0, Z_i) = \begin{cases} 1, p_{ij} = p_{0j} \\ 0,\ p_{ij} \neq p_{0j} \end{cases} \quad (1)$$

2) Values of crisp numbers are two points in the continuous space of feature C_j. These values are expressed as mathematical numbers. For instance, values of "project value" for historical and target cases could be 500.000$ and 650.000$, respectively. Thus, the distance-based method can be employed to measure the similarity between historical and target cases. Let $\Delta(p_{ij}, p_{0j})$ represent the difference degree between p_{ij} and p_{0j}, then $\Delta(p_{ij}, p_{0j})$ is calculated as follows:

$$\Delta(p_{ij}, p_{0j}) = \frac{1}{\Delta_j'^{max}} \sqrt{(p_{ij} - p_{0j})^2}$$

$$\text{Where: } \Delta_j'^{max} = max\left\{\sqrt{(p_{ij} - p_{0j})^2}\right\} \text{ and} \Delta\left(p_{ij}, p_{0j}\right) \in [0,1] \quad (2)$$

Furthermore, the final similarity between Z_i and Z_0 concerning feature C_j calculated by using the inverse exponential function given in Eq. (3). The rationale behind the use of the inverse exponential function is that it can better match human notions of similarity as well as it can better satisfy the symmetry, reflexivity, and multiplicative transitivity (Billot, Gilboa, & Schmeidler, 2008; Guerdjikova, 2008).

$$Sim_j(Z_0, Z_i) = exp\left[-\Delta(p_{ij}, p_{0j})\right] \quad (3)$$

3) In the fuzzy linguistic variable format, values are linguistic variables such as high, extremely high, high, medium, low, extremely low, definitely low. Each of these linguistic variables is represented by a triangular fuzzy number and these numbers are (0.83, 1, 1), (0.67, 0.83, 1), (0.5, 0.67, 0.83), (0.33, 0.5, 0.67), (0.17, 0.33, 0.5), (0, 0.17, 0.33) and, (0, 0, 0.17), respectively. The retrieval mechanism measures the similarity between these triangular fuzzy numbers by using Eqns (4) to (5). In the following equations, p_{ij} and p_{0j} are denoted as $p_{ij} = \left(p_{ij}^a, p_{ij}^b, p_{ij}^c\right)$ and $p_{0j} = \left(p_{0j}^a, p_{0j}^b, p_{0j}^c\right)$.

$$\Delta(p_{ij}, p_{0j}) = \frac{1}{\Delta_j'^{max}} \sqrt{(p_{ij}^a - p_{0j}^a)^2 + (p_{ij}^b - p_{0j}^b)^2 + (p_{ij}^c - p_{0j}^c)^2}$$

$$\text{Where: } \Delta_j'^{max} = max\left\{\sqrt{(p_{ij}^a - p_{0j}^a)^2 + (p_{ij}^b - p_{0j}^b)^2 + (p_{ij}^c - p_{0j}^c)^2}\right\} \quad (4)$$

$$\text{and } \Delta\big(p_{ij}, p_{0j}\big) \epsilon [0,1]$$

Consequently, the similarity between the historical case Z_i and target case Z_0 concerning fuzzy linguistic variable C_j is calculated by using the formula given by

$$Sim_j(Z_0, Z_i) = exp\big[-\Delta(p_{ij}, p_{0j})\big] \quad (5)$$

Finally, all local similarities calculated as indicated above are aggregated by using weights in Table 4. The following formula was used for this purpose:

$$Sim\big(Z_0, Z_i\big) = \sum_j w_j * Sim_j(Z_0, Z_i) \quad (6)$$

6.3. Features and benefits of CBRisk Tool

The latest version of the tool is available at www.cbrisk.site . In total, the tool's user and admin panel contain "35" screens and several of these screens were shown in Figures 7 and 8. Some features and potential benefits of CBRisk are summarized as follows:

1) Risk identification based on similar projects and risk catalogue: The major idea in the paper is that similar risks tend to re-occur in similar projects, and the decision-makers can use post-project risk event histories to give more reliable decisions in similar projects (Dikmen et al., 2008). However, this cannot be achieved in the absence of a CBR based tool since measuring similarity could be a challenging task for decision-makers based on their intuitions. Thus, the tool retrieves 5 of the most similar projects from the database.
2) Knowledge capture: Previous sections widely discuss the potential benefits of capturing risk-related knowledge of projects to RM of the forthcoming projects. Thus, this tool uses the principles of machine learning so that it has a dynamic and continuously developing database. In this way, it is ensured that the tool will not be out of date within the time.

3) RM at every stage of the project: Dikmen et al. (2008) pinpointed that RM should not be perceived as a one-time activity performed at the beginning of the project. Contrarily, they emphasized that RM must be performed continuously. Thus, the project is divided into three main stages. These are pre-project, during the project, and post-project phases as depicted in Figure 3. After the final risk register is prepared by the risk manager at the pre-project stage, the risk-related knowledge within the risk register is continuously updated during the project and post-project stages. This updated information includes the actual impact of the risks, new risks, responses given to these new risks, and the effectiveness of response plans. Then, this knowledge is stored within the database for the forthcoming projects.
4) Guidance on different RM processes: The tool is capable of assisting the risk manager at the pre-project stage by estimating the probability and impact of each risk. In practice, expert judgment was often used to estimate the probability of risk events (Dikmen et al., 2008). PMBOK (2018) pinpoints that subjective probabilities determined based on an expert judgment can cause bias and this bias should be taken into account for accurate estimates. To provide a reference point to the risk manager, the probability of each risk is determined by counting its occurrence within the five retrieved projects. For instance, if the risk of "late delivery" occurred in two projects out of five, the probability rating is determined as 2 (frequency = 2/5 = 40%). This number can be used as a reference by the risk manager while assigning probability values. However, it is clear that as the frequencies do not depend on a large number of data, they may not provide reliable reference values in some of the cases. The risk manager is expected to provide the most reliable input based on his/her expert opinion. Impacts are calculated by taking a weighted average. The weight of each project is determined based on its similarity with the new project. However, the point worthy of note is that the tool does not provide a quantitative model for risk analysis. Contrarily, the tool aims to provide risk-related information based on similar projects so that decision-makers can make a more accurate analysis of the probability and impact of risks. In other words, probabilities and impacts calculated by the tool should be checked and if necessary, edited by the authorized users such as the risk manager. In this respect, user intervention is possible at each step of the tool. Another guidance of the tool is that it can help to generate response plans. Risk

responses given to each risk are retrieved by the tool and listed for the risk manager, in turn, the risk manager can check which responses are generated for a specific risk.

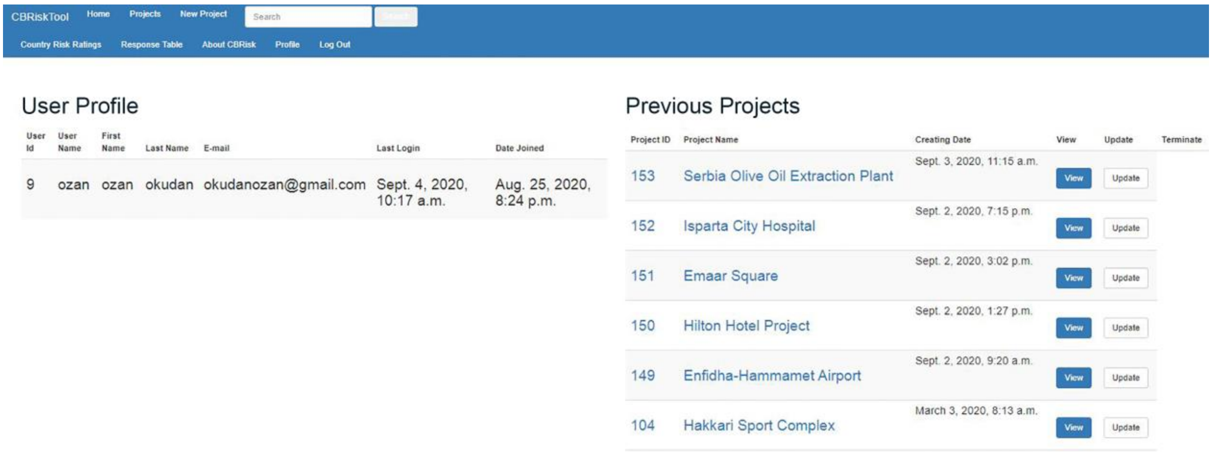
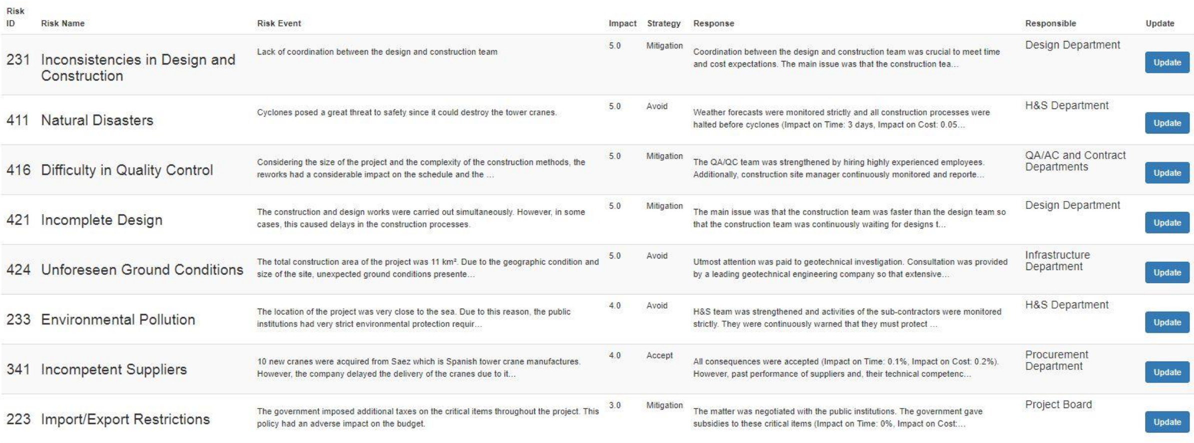


Figure 7. The main screen of the tool



Risk ID	Risk Name	Risk Event	Impact	Strategy	Response	Responsible	Update
231	Inconsistencies in Design and Construction	Lack of coordination between the design and construction team	5.0	Mitigation	Coordination between the design and construction team was crucial to meet time and cost expectations. The main issue was that the construction tea...	Design Department	Update
411	Natural Disasters	Cyclones posed a great threat to safety since it could destroy the tower cranes.	5.0	Avoid	Weather forecasts were monitored strictly and all construction processes were halted before cyclones (Impact on Time: 3 days, Impact on Cost: 0.05...	H&S Department	Update
416	Difficulty in Quality Control	Considering the size of the project and the complexity of the construction methods, the reworks had a considerable impact on the schedule and the ...	5.0	Mitigation	The QA/QC team was strengthened by hiring highly experienced employees. Additionally, construction site manager continuously monitored and reporte...	QA/AC and Contract Departments	Update
421	Incomplete Design	The construction and design works were carried out simultaneously. However, in some cases, this caused delays in the construction processes.	5.0	Mitigation	The main issue was that the construction team was faster than the design team so that the construction team was continuously waiting for designs t...	Design Department	Update
424	Unforeseen Ground Conditions	The total construction area of the project was 11 km². Due to the geographic condition and size of the site, unexpected ground conditions presente...	5.0	Avoid	Utmost attention was paid to geotechnical investigation. Consultation was provided by a leading geotechnical engineering company so that extensive...	Infrastructure Department	Update
233	Environmental Pollution	The location of the project was very close to the sea. Due to this reason, the public institutions had very strict environmental protection requir...	4.0	Avoid	H&S team was strengthened and activities of the sub-contractors were monitored strictly. They were continuously warned that they must protect ...	H&S Department	Update
341	Incompetent Suppliers	10 new cranes were acquired from Saez which is Spanish tower crane manufactures. However, the company delayed the delivery of the cranes due to it...	4.0	Accept	All consequences were accepted (Impact on Time: 0.1%, Impact on Cost: 0.2%). However, past performance of suppliers and, their technical competenc...	Procurement Department	Update
223	Import/Export Restrictions	The government imposed additional taxes on the critical items throughout the project. This policy had an adverse impact on the budget.	3.0	Mitigation	The matter was negotiated with the public institutions. The government gave subsidies to these critical items (Impact on Time: 0%, Impact on Cost:...	Project Board	Update

Figure 8. A section of final risk register belonging to Oman Muscat Airport

7. Validation of the Tool

Validation of the tool was carried out with a two-step procedure as shown in Figure 1. Initially, the research team tested the functionality of the tool by using black-box testing methods. This test was necessary to ensure that all functions integrated into the tool work properly. Within this context, 20 hypothetical projects together with their risk-related information were entered into the tool. These projects represent the risk memory of the construction companies. Then, a new project was created, and all the above-mentioned RM processes were initiated for this project as a simulation of the real case. After creating a project, the similarity measurement mechanism was firstly tested whether it is capable of retrieving similar projects or not. Initially, it is realized that the mechanism worked as expected but its response time was long. Thus, a series of efforts were made to reduce this response time to an acceptable level. Upon this development, template risk register prepared by the tool based on previous projects was tested. This template risk register should have included all risks of similar projects, probability, and impact of each risk, and lists of risk responses generated for each risk. Eventually, the template risk register passed the test. Thirdly, the tool's knowledge capture feature was tested by inserting, modifying, and deleting risk-related knowledge. The knowledge capture feature was approved by the research team and the process was terminated. However, it was detected that the system failed to save the final risk register to the database due to an error with the "Terminate" button. This bug was therefore fixed, and the test was finalized. Fourthly, authorizations given to each user role were controlled so that potential operational problems arising from unauthorized interventions are avoided. Consequently, the tool's all functions were tested under similar circumstances of engineering practice and test results revealed that all functions such as similarity measurement mechanisms and risk catalogue work flawlessly.

In the second step of the validation, the system and the process model were evaluated and validated by four experts from Turkish and European construction companies to ensure that the system meets the needs of engineering practitioners. In this respect, the second validation was carried out utilizing the methodology by Udeaja et al. (2008) and Eken et al. (2020) in this study. Three experts have been working in two different Turkish construction companies. These companies were listed in the Top 250 International Contractors list prepared by Engineering News-Record (ENR) so that these companies certainly have massive experience in international construction projects. On the other hand, the last expert has been working in an Austria-based construction company which is currently active in 19 European countries. All experts have more than ten years of experience in the CI while the last expert has 6 years of experience in the CI. Although the last expert seems to have limited experience, her opinion about the tool was crucial to test the applicability of the tool to international construction companies. All the participants were involved in RM of the construction projects to some extent. For instance, the second and third participants stated that they actively monitor the risks in their projects and record the risk-related knowledge that they captured from the project. However, all participants stated that their companies do not have an IT tool that can facilitate knowledge-based RM.

Contrarily, they reported that they use some other software such as excel which is not developed specifically for RM.

During the meeting, initially brief information about RM and the benefits of the knowledge-based RM were given to participants. After this brief information, all functions of the tool were demonstrated to participants to show how this tool can facilitate knowledge-based RM. Since the tool is constructed based on the principle of similar risks that tend to re-occur in similar projects, the similarity measurement mechanism and its accuracy were explained in detail to respondents. At the end of the meeting, the participant's opinions were asked to reveal the strength and weaknesses of the tool. The keynotes of the meeting are listed below:

i. All participants agreed that risk-related knowledge of past projects can be regarded as a catalyst for the RM of the forthcoming projects. Additionally, they pinpointed that most of the construction companies implement similar techniques and management practices so that they can hardly gain a competitive advantage in the market. Thus, they considered corporate risk memory vital know-how that can be used by construction companies to distinguish themselves from other companies within the market. "Respondent 1" stated that construction companies usually have high employee turnover due to the project-based nature of the CI. Thus, he pinpointed that corporate risk memory can eliminate the effect of employee turnover on RM.

ii. Process model shown in Figure 3 was found useful and beneficial by all experts. Especially, the idea of continuous risk management from the beginning to the end of the project was appreciated by the experts. All experts agreed that the system offers reliable results unless the data entered into the system is relevant and useful. Thus, all the participants accepted that the meetings at the post-project appraisal stage as shown in Figure 3 are key to maintain the reliability of the tool. However, "Respondent 1" underlined that experts who will participate in these meetings must have sufficient knowledge about the project. In other words, experts must be involved in all stages of the project. He stated that it might be challenging to find such an expert in the construction site since old employees are continuously replaced by new employees due to high turnover within the industry. Thus, he concluded that the reliability of these meetings could be also questionable, and companies should be aware of this issue.

iii. All participants approved that the similarity measurement mechanism provides logical and accurate results. Besides, “Respondents 2 and 3” stated that their company has currently been attempting to establish corporate risk memory, however, their system was excel-based and lacks any similarity measurement mechanism. Considering the size of this database, they accepted that it is a challenging issue to find similar projects in the absence of a similarity measurement mechanism. On the other hand, all of the respondents found project features sufficient to represent all critical areas of the construction projects. However, “Respondent 3” argued that “the availability of special construction materials in the project” could be added as an additional project feature. He emphasized that the availability of special materials poses a great risk to projects since they necessitate additional skills, machinery, and processes.

iv. All experts appreciated the tool’s ability to assist decision-makers on RM processes such as risk identification, risk analysis, and generating risk responses. “Respondent 1” proposed that the tender specialist tremendously benefits from this tool since the tool offers a template risk register based on similar past projects. “Respondents 2 and 4” stated that even inexperienced tender specialists could carry out effective RM with the guidance of this tool.

v. The tool’s risk monitor function was found sufficient to capture risk-related knowledge from the construction projects. They all agreed that the risk catalogue consists of a wide range of risks that can be emerged throughout the project's life cycle and has the potential to ease risk identification during the risk monitor process. Especially, “Respondents 4” pointed out that capturing and storing risk-related knowledge of future projects guarantee that this tool will continue to be effective in the future. However, according to “Respondent 2”, the system might show the user’s activity logs to avoid improper entry of data. Besides, “Respondent 2” believes that tracking activity logs of the users can be used to encourage employees to make contributions to the system since it makes rewarding highly active users possible.

vi. All respondents favoured the web-based structure of the tool. “Respondent 3” stated that they have used several web-based systems in his company and employees in the head office can easily access the system to get information even about overseas construction projects. Additionally, “Respondents 2” appreciated that the tool does not require a huge amount of technological investments. He emphasized that even medium-sized companies can implement this system since it requires modest investment. On the other hand, “Respondent 1” suggested that this tool could be further integrated into ERP or BIM systems to increase its effectivity

vii. The interface of the tool was found user-friendly by all experts. They clarified that the simplicity of the interface is crucial since most of the employees working in a project have strict time limitations; therefore, it is difficult for them to spare time for learning complex interfaces.

Additionally, a small questionnaire survey was conducted on the participants where they were asked to evaluate the expressions given in the following table based on the “1-6 scale”. Consequently, it can be asserted that respondents consider CBRisk as a promising tool.

Table 6. Answers of the participants to questionnaire survey

	Respondents				
Survey Questions	1	2	3	4	Avg.
The process model is complete and suitable to improve RM of construction projects.	5	5	6	6	5.5
The process model supports all RM processes of construction projects.	5	5	4	5	4.75
The process model is applicable to engineering practice	6	5	5	5	5.25
My general opinion about the proposed process model is positive	6	5	6	6	5.75
The logic of similar projects tends to face similar risks is correct and useful	5	5	6	6	5.5
Project features are enough comprehensive to represent construction projects detailly	5	5	5	5	5
Overall, the similarity measurement works accurately	5	6	4	6	5.25
Predefined user roles are sufficient to operate the system effectively and efficiently	5	5	6	5	5.25
Risk catalogue presents a wide range of risks that can be emerged throughout the project’s life cycle	5	5	5	5	5
How well does the system aid decision-makers during the RM of the construction projects at the pre-project stage?	6	6	6	6	6
How well does the system achieve the concept of capturing the information related to risk?	5	5	6	5	5.25
How well is the interface of the system?	5	6	6	6	5.75

How well does the system help companies to establish corporate risk memory?	6	6	5	5	5.5
My general opinion about the proposed system is positive	6	6	6	6	6

8. Summary of Findings and Conclusions

CI has historically been turbulent and arena of competition. This environment threatens the success of both companies and projects since it is seen as a major source of risks. Thus, decision-makers have to implement an effective RM to eliminate, or at least reduce adverse effects of the risks on the construction projects. Corporate risk memory has considerable potential to bolster the effectiveness of the RM. This risk memory allows construction companies to store and update all risk-related knowledge of their projects so that companies can capture their risk-related experiences and use them in forthcoming projects. Unfortunately, despite its benefits, construction management literature fails to provide a methodology or an IT tool that can fully facilitate knowledge-based RM. Thus, this study aimed to design and develop a web-based tool that can both construct corporate risk memory and facilitate knowledge-based RM. CBR is determined to be one of the best techniques since it can solve new problems by using the solutions of similar past problems. The proposed tool, CBRisk, can be used by decision-makers to carry out RM of construction projects. Similar projects in the database (Corporate risk memory) can be retrieved by the decision-makers and their risk-related knowledge could be used as a starting point for the RM of current projects. Moreover, the tool provides a systematic mechanism to capture risk-related knowledge of existing projects so that its database is continuously updated and developed to maximize its accuracy. In this respect, the CBRisk tool uses the principles of machine learning.

The functionality of the tool was initially tested by the research team. Various tests were performed by using black-box testing methods and any flaws detected during these tests were corrected immediately. During the tests, firstly, 20 hypothetical projects and their risk-related information was entered into the database. Secondly, another hypothetical project was created within the tool and all RM processes were initiated for this project. Namely, the RM of a construction project was simulated. Consequently, all functions and components passed the tests and were approved by the research team. After the functionality tests, the tool was tested by European and Turkish construction professionals. Since construction professionals are the potential users of the system, the second test was tremendously necessary to measure the performance of the tool. The opinions of the experts were collected through expert review meetings. In these meetings, all details of the tool and process model were presented to experts and then, their opinion was asked. Results of the expert review meeting revealed that risk-related knowledge of previous projects is vital know-how for the construction companies and CBRisk is a useful tool to capture and use this knowledge. The CBRisk can also strengthen the competitive position of companies by safeguarding the companies against the high-employee turnover with a formal corporate risk memory. The benefits of the knowledge-based RM process model were also verified by the experts. The results indicated that continuous RM throughout the life cycle of the project may aid decision-makers to develop proactive risk response strategies that emerge during a project. Given the fact that prevention is always better than cure, proactive response strategies are certainly the key to achieve project objectives. Experts verified that a case-retrieval mechanism is a must to facilitate effective knowledge-based RM. They stated that construction companies may have a high number of projects within their portfolio. Thus, it would be challenging to find similar projects to a forthcoming project from a large database. The similarity measurement mechanism developed in this study was verified to provide reliable results. However, results indicated that minimal modifications shall be necessary before its actual implementation in practice and can be tailor-made considering specific company needs such as the size and types of projects carried out by the company. Live knowledge capture, inter-project learning and web-based architecture had initially been considered as one of the most critical strengths of the CBRisk. The results of the expert review meeting also pinpointed that these features may have significant benefits in practice.

It is believed that this research has theoretical contributions. Research gaps in knowledge-based RM systems were identified from the literature and CBRisk was developed to fill these gaps. CBRisk was established on a web-based platform and integrated with a case retrieval mechanism to effectively capture and reuse risk-related knowledge of previous projects. CBRisk provides a solution for a cyclic RM process supporting each step of RM from risk identification to risk monitoring. Moreover, this study contributes to the literature by integrating all steps of CBR and RM for the first time. It presents a detailed answer of how a complete CBR system can be integrated into a knowledge-based RM tool, which can be used by other researchers who aim to develop similar tools. The case retrieval mechanism developed in this study provides an advanced and accurate similarity measurement system owing to the use of fuzzy logic, the use of numerous project features, and hybrid similarity measurement as proposed by Fan et al. (2014), and further be used in forthcoming studies.

CBRisk has also some practical contributions. The tool can be easily integrated into companies' IT infrastructure with minimal modifications. The RM philosophy adopted by CBRisk is in full accordance with the PMBOK (2018) which is a project management guideline widely used in project-based industries. Thus, the tool could also be adopted by other project-based industries and/or companies by modifying several sections such as project features, risk and risk response catalogues. CBRisk does not need high-performance hardware components and additional software resources to be present on a computer. The tool can easily be accessed via all web-browsers and mobile devices, requiring minimum effort to manage and maintain the system. The companies do not need to recruit additional employees since defined user roles could be assigned to positions that already exist in most of the companies. However, as pinpointed by many researchers, organizational culture might be a major barrier in the implementation of knowledge management systems. The blame culture, career concerns, avoidance of employees to admit mistakes, and lack of management support can create a significant barrier for the tool's practical implementation. Thus, companies should formulate the necessary strategies to remedy issues stemming from organizational culture. Otherwise, the benefits of CBRisk can hardly be exploited.

This study also has some limitations. Firstly, the CBRisk tool has been developed within the scope of a year-long scientific research project. Thus, the tool was coded by the research team rather than a professional software company so that it may have some shortcomings related to its interface and response time. Although the tool's functions were widely appreciated by the experts, there may be still room for improvement in these areas. The tool can be customized according to the specific needs of companies that will use this system. The second limitation could be related to the risk and risk response catalogues. Risk and risk response catalogues were developed based on extensive literature review and brainstorming. These catalogues can be modified by the users if necessary. As stated by one of the experts, the effectiveness of the tools could be further improved when it is used together with other project management tools such as BIM and ERP. Further studies could integrate CBRisk with BIM and ERP tools. Additionally, the question of how much time and effort should be spent to develop and implement knowledge-based RM tools remains unanswered, hindering the adoption of these tools in construction companies. Thus, future studies shall investigate the feasibility of deploying such a system by considering short-term costs and long-term benefits.

9. Acknowledgment

This work was supported by the Research Fund of the Yildiz Technical University. Project Number: FYL-2020-3823.

The authors would also like to thank PhixAi for aiding tool’s development process.

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