

REPUBLIC OF TURKEY
YILDIZ TECHNICAL UNIVERSITY
GRADUATE SCHOOL OF SCIENCE AND ENGINEERING

**A KNOWLEDGE-BASED RISK MANAGEMENT TOOL FOR
CONSTRUCTION PROJECTS USING CASE-BASED REASONING**

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MASTER OF SCIENCE THESIS

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*Dedicated to my family
and my beloved girlfriend*



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LIST OF SYMBOLS

$C.I$	Consistency Index
$C.R$	Consistency Ratio
V	Degree of Possibility
Δ	Difference Degree
n	Dimension of a Matrix
λ	Fuzzy Eigen Value
S	Fuzzy Synthetic Extent
Sim	Global Similarity
Sim_j	Local Similarity
$R.I$	Random Consistency Index
W	Weight Vector

LIST OF ABBREVIATIONS

AHP	Analytical Hierarchy Process
ANN	Artificial Neural Network
APM	Association for Project Management
BIM	Building Information Modelling
CBR	Case-based Reasoning
CI	Construction Industry
CM	Cognitive Map
ENR	Engineering News-Record
ERP	Enterprise Resource Planning
Fuzzy LV	Fuzzy Linguistic Variables
IT	Information Technologies
KM	Knowledge Management
MCDM	Multi-criteria Decision Making
RBS	Risk Breakdown Structure

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

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Department of Civil Engineering

Master of Science Thesis

Advisor: Assoc. Prof. Dr. Cenk BUDAYAN

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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 an 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, knowledge-based risk management, risk management, knowledge management, Case-based Reasoning



İnşaat Projeleri İçin Vaka Temelli Örneklemeye Kullanan Bilgi Tabanlı Bir Risk Yönetimi Aracının Geliştirilmesi

Ozan OKUDAN

İnşaat Mühendisliği Bölümü

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İnşaat projeleri, çoğunlukla dış etkenlere karşı savunmasızdır ve projeyle ilgili belirsizlikler nedeniyle genellikle karmaşık ve yüksek riskli projeler olarak kabul edilir. Risk yönetimi (RY), inşaat sektöründe faaliyet gösteren şirketler için kritik bir başarı faktörüdür. RY, riskle ilgili bilginin etkin bir şekilde yönetilmesini gerektiren bilginin yoğun olarak kullanıldığı bir süreçtir. Bilgiye dayalı RY süreçlerini desteklemek için araçlar geliştirmek için halihazırda bazı araştırmalar yapılmış olsa da, bu araçların çoğu, anlık bilgi yakalama, bilgi paylaşımı için web tabanlı platform ve geçmiş projelerden elde edilen tecrübeyi etkili kullanma gibi bazı kritik özellikleri göz ardı etmektedir. Ayrıca, risk tanımlama, analiz, yanıt ve izleme gibi RY aşamalarının biri veya birkaçı mevcut çalışmalar tarafında göz ardı edilmiştir. Bu nedenle, bu çalışma, vaka temelli örneklemeye (CBR) yoluyla bilgi tabanlı bir RM aracı (yani CBRisk) geliştirerek bu eksilikleri gidermeyi amaçlamaktadır. CBRisk, döngüsel RY sürecini destekleyen ve kapsamlı bir proje özelliklerini dikkate alan etkili bir web tabanlı bir araç olarak geliştirilmiştir. Son olarak, geliştirilen araç kara

kutu testi ve odak grup görüşmeleri yapılarak değerlendirildi ve etkinliği onaylandı. Sonuçlar, CBRisk'in inşaat projelerinde RY'nin etkinliğini artırmak için önemli bir potansiyele sahip olduğunu ve minimum modifikasyonla diğer proje tabanlı endüstrilerde kullanılabileceğini göstermiştir.

Anahtar Kelimeler: Yapay Zeka, bilgi tabanlı risk yönetimi, risk yönetimi, bilgi yönetimi, Vaka temelli örnekleme.



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 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 during a project becomes a vigorous concept for construction companies.

PMBOK [1] 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 [1] 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 [2] 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 [2] 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 [3]. PMBOK [1] 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. [4] 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 [5]. In practice, RM in 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, the 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 [4]. Atkinson et al. [6] 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 [7]. 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 [8]. 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 [9].

Many researchers argued that construction companies can barely capture, store, and disseminate knowledge to optimize the RM of forthcoming projects [10], [11]. Although the benefits of knowledge-based systematic RM are widely discussed in the literature [12]–[15], 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 [9], [16]–[19]. In literature, efforts have been devoted by several authors to establish systematic knowledge-based RM tools such as Dikmen et al. [4], Yildiz et al. [3], and Fan et al. [20]. However, each tool or approach has its own assumptions and methodological drawbacks.

This thesis, 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 [21]. 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.

1.1 Literature Review

1.1.1 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 [1], [22], 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 [8], [9], [23], 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 [24]. 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 [25]–[27]. 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 [25]. 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 [28]. Considering that organizations can develop new knowledge by combining and sharing lessons-learned across projects [29], 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 [4], [30]. Finally, as Eken et al. [31] 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. [32] and Alizadeh et al. [33], [34]. The critical evaluation of existing knowledge-based RM tools with respect to identified features is presented in Table 1.1. The tools depicted in Table 1.1 are all aimed at facilitating knowledge-based RM for project management and listed in ascending order of their publication years.



Table 1.1 Critical evaluation of the knowledge-based RM tools

Reference	Brief description	Pros	Cons					
			A	B	C	D	E	F
Tah and Carr [35]	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 [36]	A knowledge-based risk identification system in large infrastructure projects	Capable of improving the responsiveness of existing knowledge-based approaches to project attributes		X	X	X	X	X
Choi et al. [37]	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. [25]	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. [4]	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. [38]	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. [39]	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. [40]	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. [3]	A knowledge-based risk mapping tool for systematically assessing risk-related variables	Supports decision-making at the bidding and contingency estimation phase Introduces a novel methodology to estimate potential risk paths based on previous projects' knowledge	X	X	X	X	X	X
Ding et al. [41]	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.

1.1.2 Critical Evaluation of CBR-Based RM Support Tools and Models

CBR is a cyclic process that consists of 4 steps. These steps are Retrieve, Reuse, Revise, and Retain [42]. These steps are also known as ‘the four REs’ [43]. Retrieve, which is a process of searching and determining the most similar and relevant case or cases [42], [44], is seen as the core and the most important step in any CBR systems [21]. 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 [43]. 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 [45]. 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 [46]. 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 [45], [47], [48]. 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 [46], [48]. 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. [45] and Kong et al. [49] consider only crisp numbers and crisp symbols, which, in turn, cause abovementioned drawbacks. However, Fan et al. [46] 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 1.2, the existing studies of knowledge-based RM tools/methods using CBR were reviewed with respect to these features.

Table 1.2 Critical evaluation of previous CBR tools and models developed to support RM

Reference	Brief description	Pros	Cons		
			A	B	C
Kumar and Viswanadham [50]	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. [51]	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. [52]	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. [21]	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. [20]	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. [43]	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. [53]	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. [54]	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.

1.2 Objective of the Thesis

The research questions identified at the start of the current thesis 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. What are the project characteristics that affect the risk occurrence of construction projects?
4. Can CBR be used to develop a tool that effectively supports a knowledge-based RM process?

To address the mentioned research questions, this thesis has the following objectives.

1. The first aim of this thesis is to determine features to develop an effective and efficient CBR-based tool to support the RM process.
2. By conducting an in-depth literature review, this thesis aims to reveal research gaps that exist in the current body of knowledge.
3. The third aim of this thesis is to identify the characteristics of the construction projects and the effects of these characteristics on the occurrence of the risks based on the Fuzzy Analytical Hierarchy Process (AHP) analysis.
4. Final and the main objective of this thesis is to develop a knowledge-based RM tool that supports the knowledge-based RM approach. By doing so, this study also demonstrates how a CBR can be an effective method to support knowledge-based RM processes.

1.3 Original Contribution

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. [3]) 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 1.2. 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.

Given the significance of the abovementioned research gaps, this thesis is believed to have substantial originality and novelty. In this respect, this study has a substantial contribution to the existing body of knowledge as well as many practical implications.



RESEARCH BACKGROUND AND MOTIVATION

2.1 Fuzzy AHP and MCDM Process

Decision-makers have to make many decisions in their professional lives. These decision-making processes usually include various sets of alternatives and the criteria for choosing one alternative over other alternatives. Here, the biggest challenge for decision-makers is deciding in the presence of the conflicting criteria. The term conflicting criteria are described as the criteria which are inversely proportional to each other. Cost and quality, for example, are the conflicting criteria. It is unlikely to have the highest quality of an alternative at the cheapest price. Thus, a decision-maker has to find the optimum alternative which best fits his/her needs. To overcome these issues and make correct decisions, Multi-criteria decision making (MCDM) has long been the focus of the decision-makers [55].

MCDM is not a method alone. By contrast, MCDM is a term used to describe the nature of decision making. Many MCDM methods exist in literature to aid decision-makers such as the AHP, and TOPSIS. These methods have been applied to the integrated manufacturing systems [56], evaluations of technology investment [57], water, and agriculture management [58], [59].

The AHP was developed by Saaty [60] and became one of the most popular multi-criteria decision-making methods [61], [62]. The method decomposes a decision-making problem into a system of hierarchies of objectives, attributes (or criteria), and alternatives. The mechanism of the AHP includes decompositions, pairwise comparisons, and priority vector generation and synthesis. The main reason behind the popularity of AHP is its ability to handle intangibles presented in any decision-making process. Computational easiness is also another advantage of the AHP. Owing to its comprehensible mathematical calculations, the AHP became widely known among the decision-makers who usually have little time to learn new methods [63]. Other advantages of AHP are listed as follows: (1) AHP can measure the consistency in the pairwise comparison of the experts. In this respect, AHP is unprecedented. (2) Its hierarchical structure allows decision-makers to

visualize the critical aspects of a problem and ease the decision-making process; (3) the AHP can be integrated with the other operation research techniques to deal with more difficult problems; (4) Both qualitative and quantitative data can be analyzed using AHP [64], [65]. However, on the other hand, AHP is not capable of using linguistic variables so that the experts have difficulties in reflecting their opinions on a 1-9 scale [63]. Although the use of the discrete scale of 1-9 for pairwise comparison helps to simplify the mathematical calculations, it reduces the effectiveness of AHP. Thus, AHP is not recommended to deal with ambiguous problems [63].

The decision-making problems with a high level of complexity cannot be picturized quantitatively. However, human brains have a unique feature that can handle these problems by using imprecise knowledge rather than precise. The fuzzy set theory is capable of imitating this unique feature of the human brain. In other words, the fuzzy set theory proposed by Zadeh [66] adopts a similar mechanism to human reasoning which can generate decisions using approximate and uncertain information. The fuzzy set theory can make a mathematical representation of the uncertainty and vagueness to provide a formalized tool for dealing with the imprecision. In other words, the fuzzy set theory can eliminate the vagueness of human thought. The traditional computing methods, however, cannot provide reliable solutions when certain and precise knowledge is not available. Thus, the fuzzy set theory paved the way for the solution to many engineering problems owing to that knowledge can be expressed more naturally by using fuzzy sets. Fuzzy set theory is not a single method that can be used to solve decision-making problems. Any crisp method or theory could be fuzzified to improve the method's ability to deal with vagueness. Any fuzzified methodology is stronger to solve real-world problems since some degree of imprecision and noise exist in almost all real-world problems. Besides, the use of linguistic variables is another benefit of the fuzzy logic application, where linguistic variables such as "large," "medium," are used rather than the number (E.g. Likerts' scale) [61]. For instance, respondents can reflect his/her judgment better in comparison with the numbers. Thus, fuzzy AHP, a fuzzy extension of the AHP, was developed to overcome the abovementioned drawbacks of AHP by Chang [67]. Both AHP and fuzzy AHP methods are used to capture experts' opinion, however, fuzzy AHP handles the impreciseness of the humans' judgments in a more effective way than the conventional AHP [68].

2.2 Risk

Risk is often defined as an undesirable event with unknown probability and impact. Just like many project-based industries, the construction industry is deemed a highly risky industry due to a dynamic and turbulent environment that leads to a high degree of uncertainty [69]. This risky nature of the construction industry can even adversely affect the performance of construction projects [35]. Thus, effective risk management is key to boost the performance of construction projects. Risk management is a repetitive process, and it is crucial to eliminate and control the risks [70]. The first step of this process is identifying risk factors, followed by an assessment of risk impacts on the project. The last step is determining the necessary strategies to minimize the negative consequences of the risks [25], [71], [72]. Risk identification is the first and most crucial step in risk management [72] since all following phases are conducted based on identified risk factors. In other words, the further steps of risk management become ineffective when risks are identified improperly. In order to avoid deviation from the project objectives, risk management should be carried out throughout the project life cycle.

2.2.1 Risk Identification

The risk management process starts with risk identification. This step is performed to identify potential sources of risk and uncertainty that exist within a project [73]. In the construction industry, the risks are identified by using generic checklists and breakdown structures. HM Treasury [78] stated that risk identification is performed in two phases. These phases are initial risk identification and continuous risk identification. At the beginning of the project, the risks should be identified and the parties should be aware of these risks throughout the project. Initial risk identification can be considered more difficult than continuous risk identification since the information about the project is very limited and imprecise at the pre-project stage. In addition, initial risk identification is very important, since the companies should prepare bids and schedules before the start of the project. At the pre-project stage, the project risks are initially identified based on the experiences of the decision-makers that they gain from their previous projects. In other words, the probability of having similar risks is very high in two projects which share many similarities. Also, the country conditions in which the project is affected should be considered as an important factor that can affect the occurrence of the risks [70], [71].

Other factors which influence the occurrence of the risks is a company's profile [70], [71].

2.2.2 Risk Assessment

Risk assessment is the process of determining the probability and impact of risks. Kaplan and Garrick [79] proposed that in a risk assessment these questions; namely "What can go wrong?", "What is the likelihood?", "What are the consequences?" should be asked and accurate answers should be investigated. Different studies develop quantitative and qualitative methods for risk assessment. Some of the quantitative approaches are Monte Carlo simulation, MCDM, AHP and system dynamics [80]. All of these tools require quantitative data to assess the risk of a project, in other words, the accuracy of these sophisticated tools depends on the quality of the data. However, due to the unique nature of construction projects, it is very challenging to collect statistical data that can be used for the prediction of probability and impact of risk events. Even if the data is available, its quality is usually not at the desired level to make precise decisions about the risk events. Due to this limitation, recently, many risk assessment approaches have been developed based on qualitative methods instead of quantitative methods [81]. For instance, Sadeghi, Fayek et al. [82] suggest using fuzzy logic to develop a fuzzy Monte Carlo simulation framework for risk assessment of construction projects. Nieto-Morote and Ruz-Vila [81] proposes a risk assessment methodology based on Fuzzy Sets Theory and the Analytical Hierarchical Process by involving the inconsistency of fuzzy preference relations.

2.2.3 Risk Response

Risk response is the process of selecting a proper strategy to reduce or eliminate the probability and/or impact of a risk event [83]. Raftery [75] proposed four risk response strategies, namely risk elimination, risk transfer, risk retention and risk reduction. Risk elimination is not a popular strategy in the construction industry [84], since the elimination of all risks is a very expensive process. The contractors can effectively manage project risks by mainly focusing on two strategies. Firstly, they can transfer the risks to another party. For instance, the contractors can transfer some of the project risks by hiring subcontractors and/or transfer the financial risks to insurance companies. The contractors can also retain the risks by examining their severity and likelihood. In other

words, the companies can accept the consequences of a risk whose probability of occurrence is low and the impact is not high. Accordingly, there are two retention methods, active and passive. In active retention, the contractors are aware of the risk and they deliberately retain the risk after calculation of the possible losses and costs of precautions for handling the risk [84]. In passive retention, the contractor reduces the likelihood and severity of the risks by taking precautions. Edwards and Bowen [85] claim that the risk should be checked first to determine if the risk can be reduced before applying the risk response methods. Besides, Retention is a widely used risk response strategy among the other risk response strategies [84], [86]. Fan, Lin et al. [83] criticized the studies about risk response in the literature since they are limited to opinion-based discussion and case studies. Additionally, most of the studies just reviewed and suggested risk response strategies for specific project types. They suggested that the dimensions and characteristics of the projects should also be considered in selection risk response.

2.2.4 Risk Monitor

Risk monitor is the last step of the risk management process. Risk monitor is “the process of implementing a risk response plan, tracking identified risks, monitoring residual risks, identifying new risks, and evaluating the effectiveness of risk management processes throughout the project” [81]. To apply this step effectively, a regular monitoring process where the effectiveness of the response plan is evaluated and the required adjustments to the plan are determined should be developed. In addition, the risk responses can lead to new potential risks and threats, and the responded risks can evolve into threats [87]. Therefore, risk monitor is a very important stage and it should be performed continuously and timely.

2.3 Knowledge

Knowledge is a combination of information and understanding and reasoning with expertise and skills acquired by a person through experience or education [88]. This definition underlines the significance of humans in transforming information and data into knowledge. However, it should be well emphasized that the terms of knowledge and information can not be used interchangeably since knowledge is a much broader term than information [89].

Explicit and tacit are the two types of knowledge. The explicit knowledge can be communicated externally so that systematic knowledge management systems can capture it [90]. Organizational documents such as reports, agreements, manuals, patents present a convenient medium to store and transfer explicit knowledge. For instance, organizations can effectively capture explicit knowledge by examining these organizational documents [91]. On the other hand, tacit knowledge is not document or record-based knowledge. Contrarily, the experience of all employees forms the tacit knowledge of a company. Thus, tacit knowledge is affected by many intangible factors, such as individual beliefs, perspective, and the value system. Since tacit knowledge mainly stems from the personal knowledge and experience of employees, it is very challenging to formalize, store and disseminate [89]. Despite this challenge, tacit knowledge is a very precious knowledge source and the key to achieving competitive advantage when compared with the potential of explicit knowledge. The reason is that tacit knowledge is difficult to imitate and essential to use explicit knowledge [92]. Consequently, many organizations and researchers have paid utmost attention to the management of tacit knowledge [93].

Explicit knowledge can be retrieved by examining the available records so that it can easily be captured and reused compared to tacit knowledge. Nonetheless, there are also problems encountered during the utilization of explicit knowledge. Due to the reasons that CI is a project-based industry involving different stakeholders and is characterized by no repetitive nature of work, information cannot be fully captured and recorded [94]. At this point, information technologies can be an effective tool to record explicit knowledge. Additionally, the same information technologies can also be used to capture, store and disseminate the tacit knowledge once it is formalized by being transformed into structured information from unstructured information effectively. In this respect, information technologies can provide extremely fertile ground for companies to manage tacit knowledge.

2.4 Knowledge Management in Construction

Davenport and Prusak [95] 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 [9], [96]. To exploit the benefits of knowledge, an appropriate mechanism is needed to capture and disseminate it [9]. 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 [19], [31]. Studies on the development of KM mechanisms to improve RM are even more limited [3], [97]. 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 [31], [98], [99], construction professionals usually use their subjective judgement for risk-informed decision-making and lack a formalised process for knowledge-based RM.

This current practice in RM causes poor definitions of the project risks and vagueness about determining the most effective risk responses [100]. Besides, risk analyzers also lack a system that aids them to monitor risks throughout the project's life cycle so that construction projects become vulnerable to new emerging risks [100]. Contrarily, risk-related knowledge of the companies must be embedded in a non-human repository such as routines, databases, or structures [31], [98], [99]. In this way, the knowledge is ensured to be made available for use in RM processes. Thus, companies will certainly benefit from the effective integration of KM to RM. Briefly, construction companies should capture, store, retrieve, and disseminate risk-related knowledge of the past projects to improve the RM processes of forthcoming projects.

Some strategies can be implemented to manage knowledge effectively within a company. These strategies can be categorized as “techniques” and “technologies” [31]. 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 [101]. Technologies can provide fertile ground for articulating, storing, and sharing knowledge [102], [103]. In the construction management literature, several IT-based tools have been developed to systematize KM within construction companies [9], [31], [104]–[107]. However, the 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.

2.5 CBR as a Technique to Develop Knowledge-Based Systems

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 a 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 mindsets 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.



The research methodology utilized in this study is shown in Figure 3.1 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. 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.

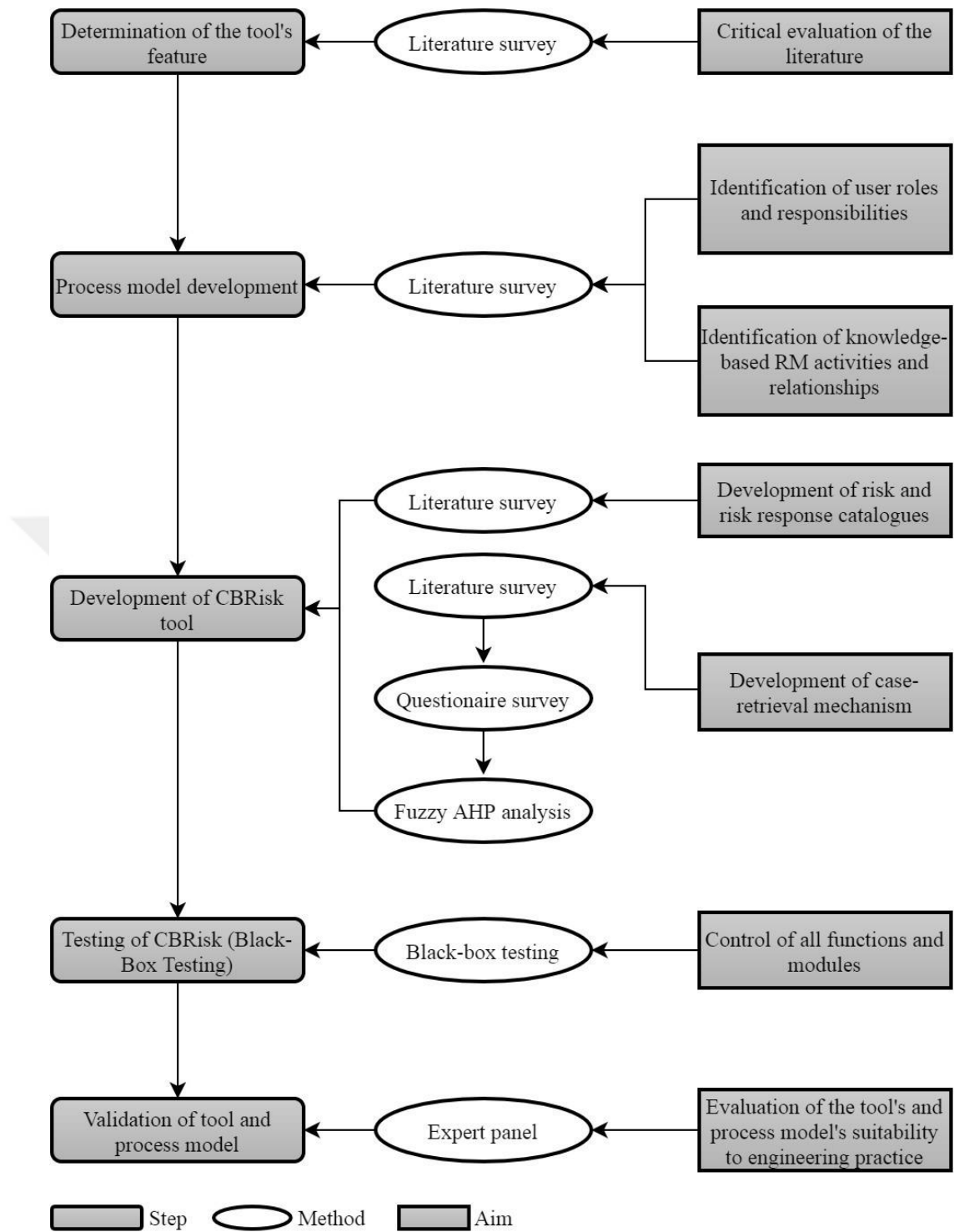


Figure 3.1 Research Methodology

3.1 Software Architecture

3.1.1 Overview of the Tool

The CBRisk tool was designed and developed in-house as a web-based application to ease its accessibility. The tool is hosted in the Apache server and coded by using the Python programming language. Since open-source products were used such as Apache and Python, the system development and operation costs were minimized, in turn, the 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 3.2. 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 3.2, the tool has its database which can also be named 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 [23], the relatively low technological investment required for the tool can be identified as an advantage.

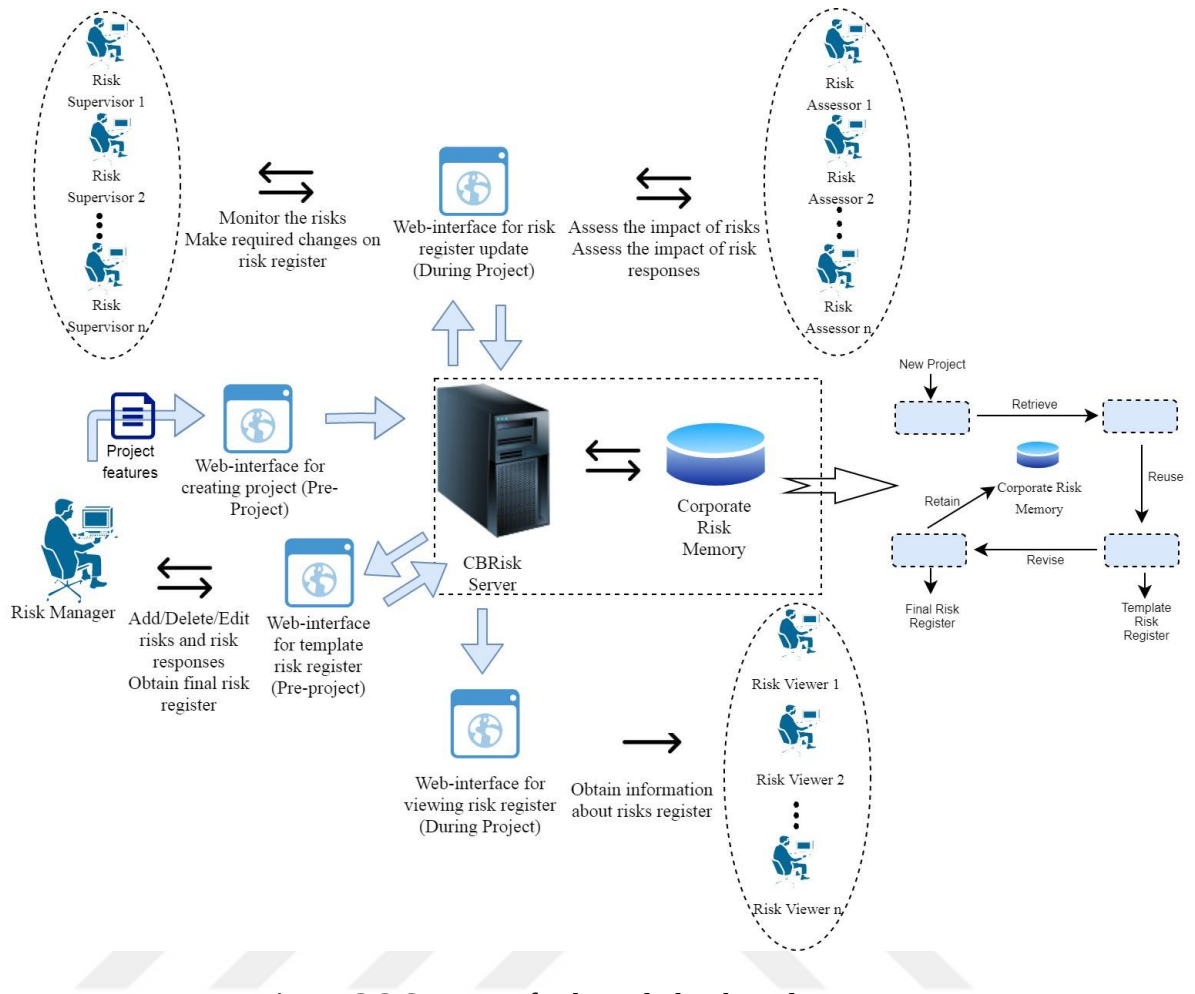


Figure 3.2 Structure for knowledge-based RM

3.1.2 Knowledge-Based RM Activities Throughout Project Life Cycle

Figure 3.3 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 [72]. 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 3.3, 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 [35], Zhi [71], and Dikmen et al. [4]. The structure of the risk catalogue is demonstrated in Table 3.1. 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 3.1 The structure of risk catalog (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 [1]. 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 [4]. 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.

3.1.3 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 3.2. 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 [31]. 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 3.4. These roles were determined by deeply examining the existing studies [4], [31]. As depicted in Figure 3.4, 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 other 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 [4]. 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 3.3, the risk manager, risk supervisor and 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.

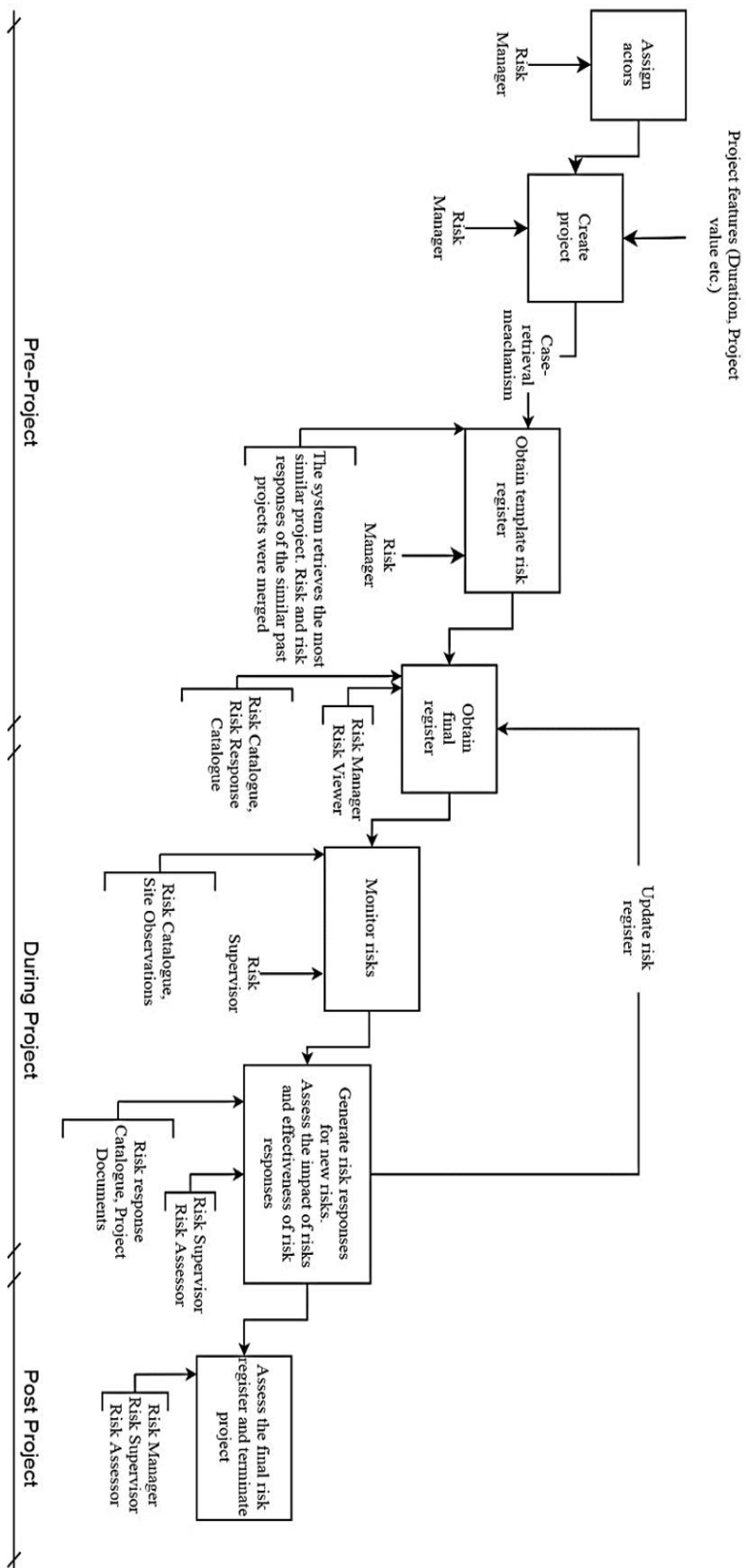


Figure 3.3 Process Model

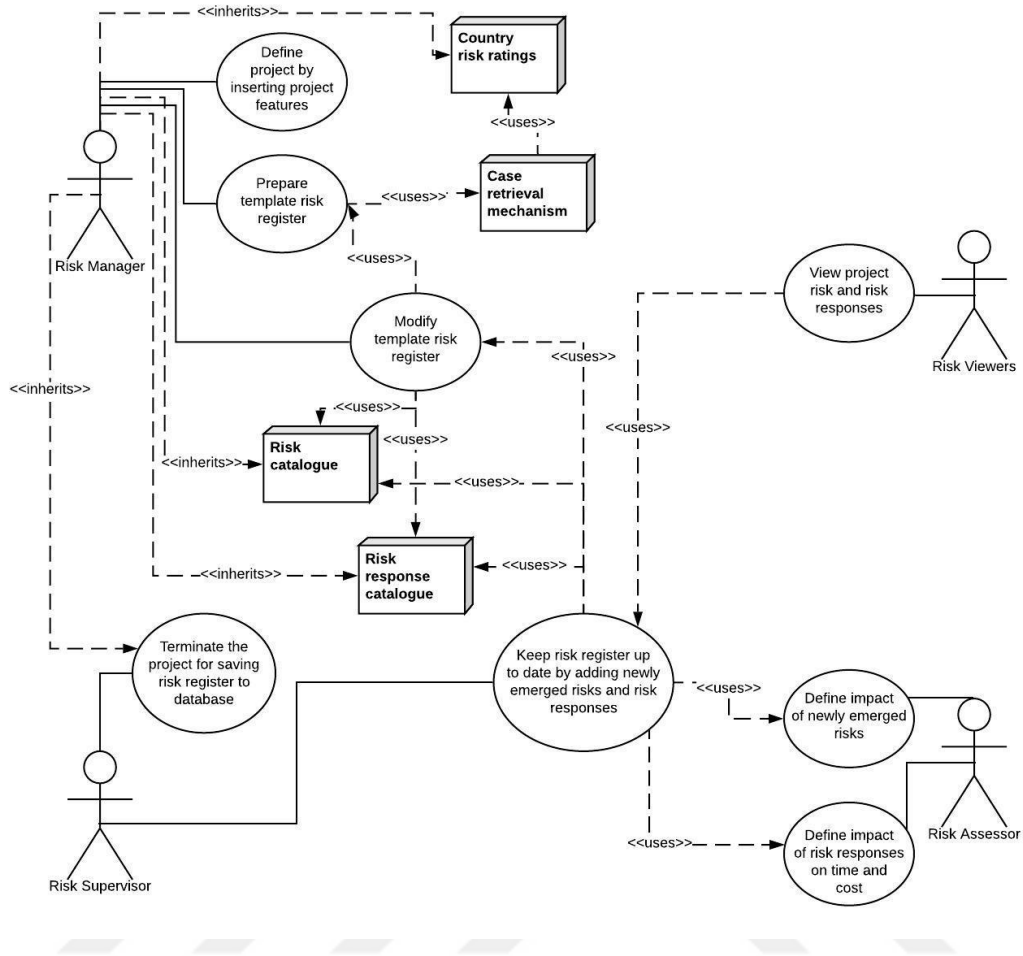


Figure 3.4 Use case diagram

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 [97]. The detailed procedure for this task is presented in Figure 3.5. 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 3.2 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 3.2 are elaborated at Sections 3.2.1 and 3.2.2, 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 3.6, 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 is continuously monitored, calculated, and entered into 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 3.2. Project features and their normalized weights (adopted from Ling et al. [108], Han et al. [109], Eybpoosh et al. [110], Fidan et al. [70], Nguyen et al. [111] and Eken et al. [31])

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 construction area	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

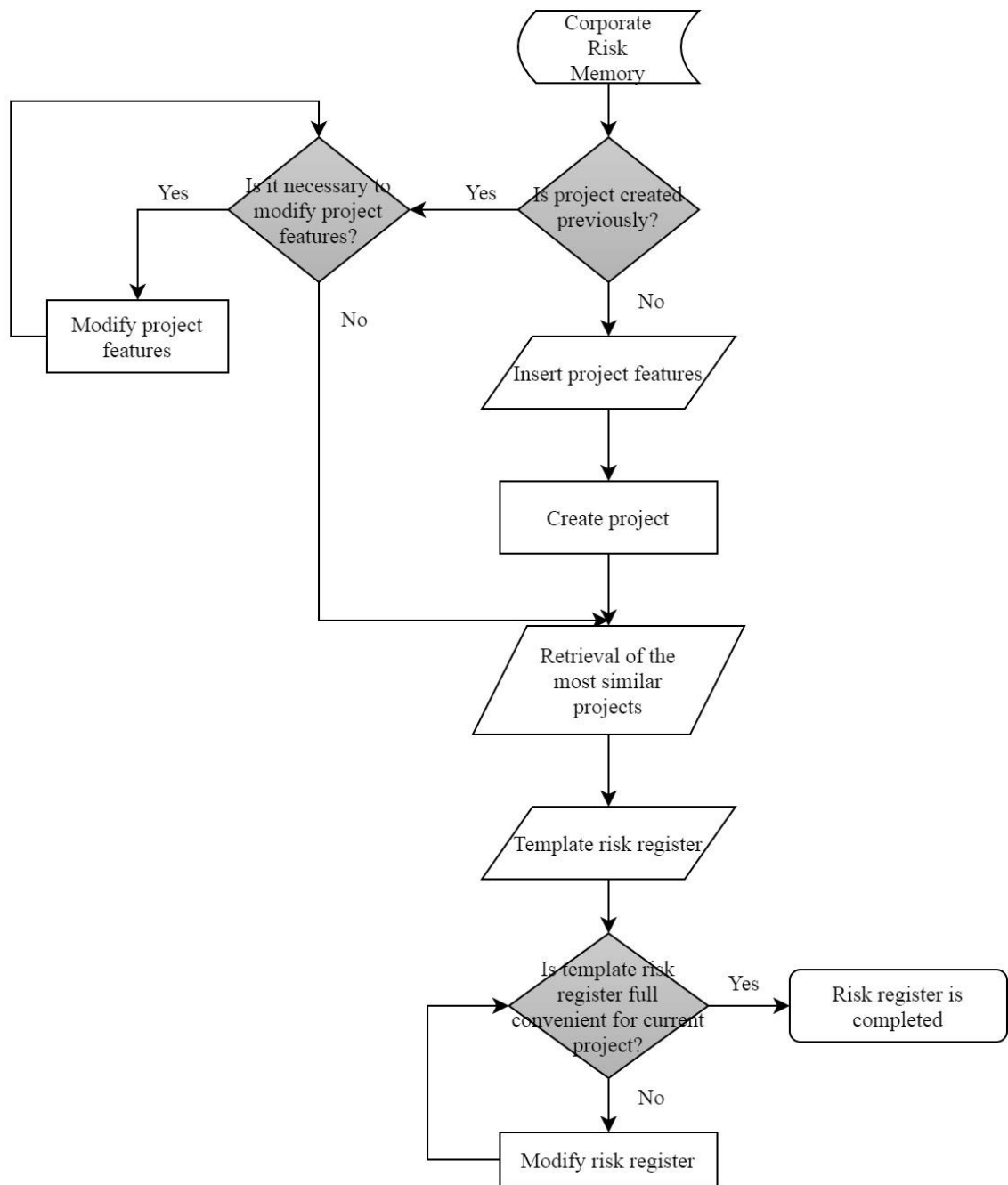


Figure 3.5 Flow chart for creating risk register at the pre-project stage

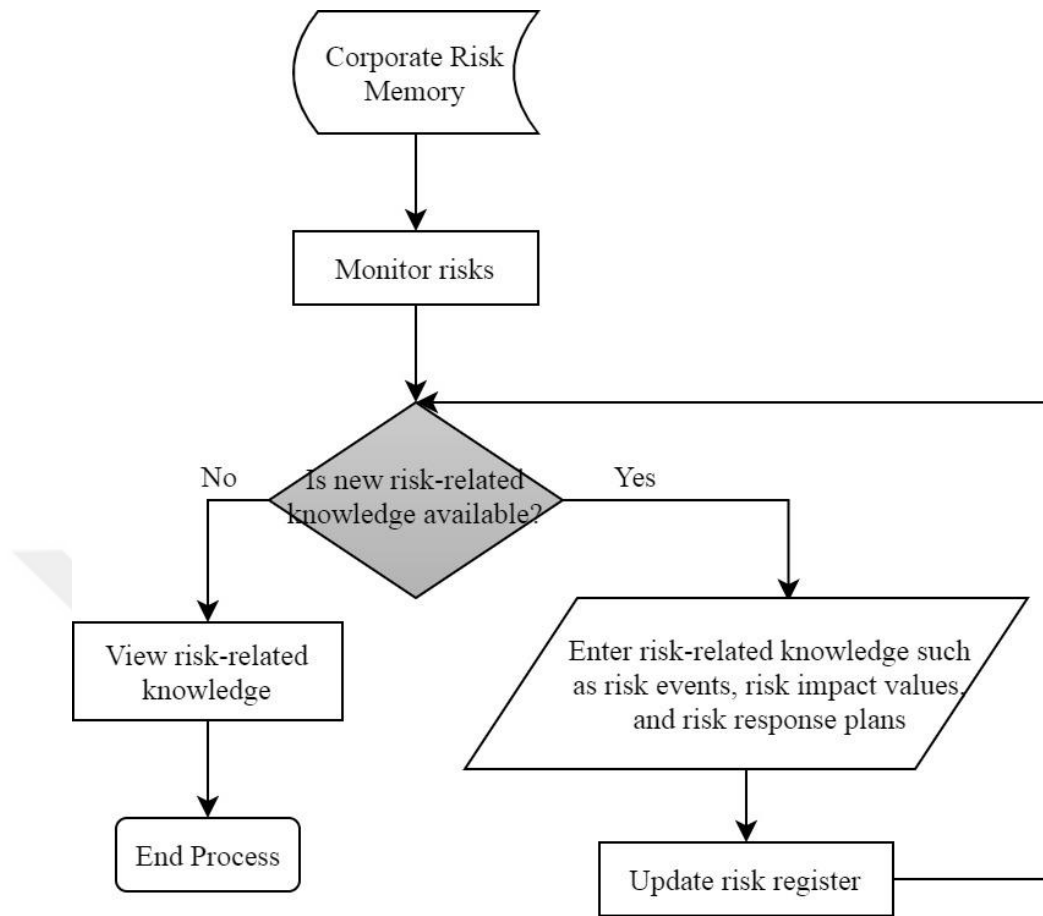


Figure 3.6 Flow chart for risk monitor processz

3.2 Development of Case Retrieval Mechanism

Case retrieval is the process of searching and determining the most similar case or cases [42], [44]. Similarity methods are used to carry out this process. In this study, the hybrid similarity measurement proposed by Fan et al. [46] 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.

3.2.1 Determination of Project Features

The accurate case retrieval mechanism is regarded as a catalyst for the performance of CBR systems [112]. 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 [46]. 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. [108], Han et al. [113], Eybpoosh et al. [110], Fidan et al. [70], Nguyen et al. [111], Eken et al. [31]. The features used in the case retrieval mechanism are shown in Table 3.2.

Although the country project feature was stated as one of the important features in the literature, studies such as Eken et al. [31] 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 [114]. 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.

3.2.2 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 (please see Appendix A). 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 3.3. 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 [115]. However, many studies pinpointed that AHP is capable of providing reliable results with a small sample size [116]. In this respect, AHP is distinguished from descriptive techniques that require laypeople rather than an expert panel [117]. By contrast, the large sample size may lead to unreliability due to the *cold-called* respondents [118]. Thus, it should be clearly stated that AHP necessitates quality data rather than a high quantity of data [119]. As seen in Table 3.3, 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 [120]. Besides, to improve the reliability of the survey, the data was collected through face-to-face interviews [121]. 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 [60] 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 3.3 Demographics of the respondents

Sample Specifications	Counts and Percentages			
<i>Parent organization</i>	Client	Main Contractor		Sub-contractor
	4 (%26.66)	10 (%66.66)		1 (%6.66)
<i>Size of the organization</i>	Small	Medium		Large
	2 (%13.33)	3 (%20)		10 (%66.66)
<i>Experience of the organization in International</i>	0-20	20-50		50-100
	8(%53.33)	4(%26.66)		3(%20)
<i>Experience of the organization</i>	0-20	20-50		50-100
	4(%26.66)	5(%33.33)		6(%40)
<i>Experience of the respondent</i>	0-10	10-15		15-30
	4(%26.66)	7(%46.66)		4(%26.66)
<i>Experience of the respondent in risk management</i>	0-5	5-10		10-25
	5(%33.33)	3(%20)		7(%46.66)
<i>Education level</i>	BSc.	MSc.		Ph.D.
	3(%20)	9(%60)		3(%20)
<i>Role of the respondent</i>	Coordinator/Ceo	Planning Specialist	Tendering Specialist	Academician
	6(%40)	3(%20)	3(%20)	3 (%20)

3.2.2.1 Methodology Followed Throughout the Analysis

This section includes the mathematical background of the Fuzzy AHP and the analysis results. The steps of Fuzzy AHP and the mathematical formulations are presented as follows.

Step 1. Development of an AHP structure: As stated above, project characteristics were extracted from the literature, and these characteristics were used to propose a model that shows the relationship between the project characteristics and the occurrence of risks. A typical AHP model structure includes main criteria and sub-criteria, which are the characteristics of the projects in this study. Namely, some characteristics were grouped with respect to their similarities, such as design-related characteristics and construction-related characteristics. Figure 3.7 shows the final structure of the AHP.

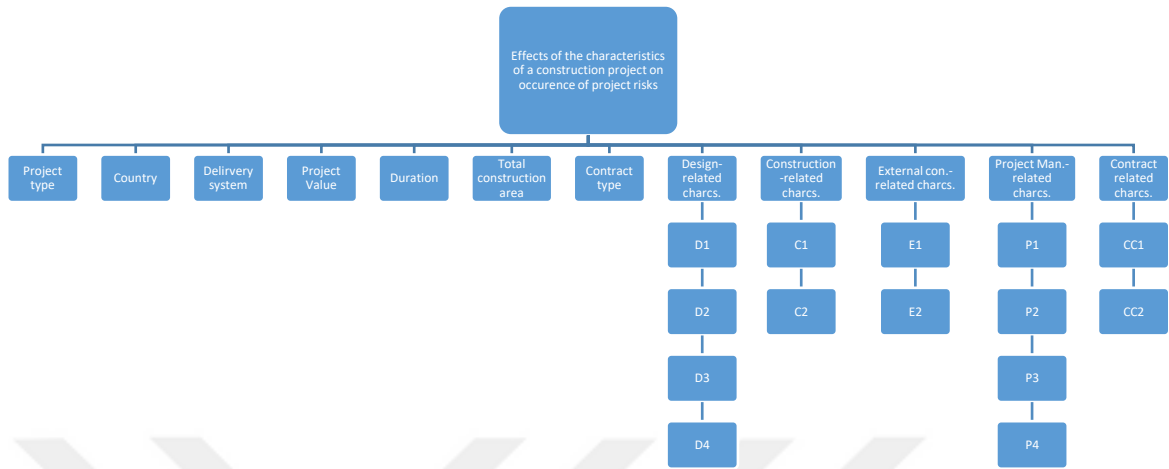


Figure 3.7 AHP model structure

Step 2. Re-arranging pairwise comparison matrices by using fuzzy numbers: This step can also be called fuzzification. Namely, pairwise comparison matrices were filled by the experts using linguistic variables, and these pairwise comparisons were re-arranged using fuzzy numbers given in Table 3.4. In other words, these matrices were fuzzified. Triangular fuzzy numbers were used for fuzzification in this study. Three parameters (l, m, u) are used to define the triangular fuzzy numbers. “l” denotes the smallest possible value, “m” indicates the most likely value, and “u” denotes the largest possible value that describes a fuzzy event.

Table 3.4 Triangular fuzzy scale (derived from Chang [67])

Linguistic variables	Crisp Number	Triangular fuzzy number	Triangular fuzzy reciprocal number
Just Equal	1	(1, 1, 1)	(1, 1, 1)
Equally Important	2	(1/2, 1, 3/2)	(2/3, 1, 2)
Weakly Important	3	(1, 3/2, 2)	(1/2, 2/3, 1)
Strongly More Important	4	(3/2, 2, 5/2)	(2/5, 1/2, 2/3)
Very Strongly More Important	5	(2, 5/2, 3)	(1/3, 2/5, 1/2)
Absolutely More Important	6	(5/2, 3, 7/2)	(2/7, 1/3, 2/5)

Step 3. Application of Chang's extent analysis method: At the previous stage, all matrices were fuzzified. Since there is no commercial software for the application of the fuzzy AHP, a MATLAB script (please see Appendix B) was coded in-house to solve fuzzy AHP matrices by following Chang's extent analysis method. This method was used to find the weights of each characteristic. Chang [67]'s extent analysis is a method of using crisp mathematical concepts to address fuzzy quantities. Let $X = (x_1, x_2, x_3, \dots, x_n)$ be an object set and $U = (u_1, u_2, u_3, \dots, u_m)$ be a goal set. Chang's extent analysis method dictates that extent analysis for each goal, g_i is performed, respectively. Firstly, the value of the fuzzy synthetic extent should be calculated as follows:

$$S_i = \sum_{j=1}^m M_{gi}^j \times \left[\sum_{j=1}^n \sum_{j=1}^m M_{gi}^j \right]^{-1}; \quad (3.1)$$

$$\sum_{j=1}^m M_{gi}^j = \left(\sum_{j=1}^m l_j, \sum_{j=1}^m m_j, \sum_{j=1}^m u_j \right); \quad (3.2)$$

To calculate $\left[\sum_{j=1}^n \sum_{j=1}^m M_{gi}^j \right]^{-1}$, perform the fuzzy addition operation of M_{gi}^j ($j = 1, 2, \dots, m$) values such that:

$$\left[\sum_{j=1}^n \sum_{j=1}^m M_{gi}^j \right] = \left(\sum_{j=1}^m l_j, \sum_{j=1}^m m_j, \sum_{j=1}^m u_j \right) \quad (3.3)$$

And then the inverse of the vector in Eqn (3) is calculated as follows:

$$\left[\sum_{j=1}^n \sum_{j=1}^m M_{gi}^j \right]^{-1} = \left(\frac{1}{\sum_{j=1}^n u_i}, \frac{1}{\sum_{j=1}^n m_i}, \frac{1}{\sum_{j=1}^n l_i} \right) \quad (3.4)$$

Finally, the value of the fuzzy synthetic extent is calculated, and the degree of possibility was obtained using the value of the fuzzy synthetic extent. The following equations, Eqn

(5), Eqn (6), Eqn (7) are used to calculate probability values. After obtaining the possibilities, the weight vectors were calculated, and eventually, the normalized weights vector was calculated to determine the weight of each project feature.

The degree of possibility of $M_2 = (l_2, m_2, u_2) \geq M_1 = ((l_1, m_1, u_1))$ is defined as:

$$V(M_1 \geq M_2) = \sup[\min(\mu_{M_1}(x), \mu_{M_2}(y))] \quad (3.5)$$

When a pair (x, y) exists such that $x \geq y$ and $\mu_{M_1}(x) = \mu_{M_2}(y) = 1$, then $V(M_1 \geq M_2) = 1$. Therefore, the degree of the possibility is as follows, since M_1 and M_2 are convex fuzzy numbers:

$$V(M_1 \geq M_2) = 1, \text{ if } m_1 \geq m_2; \quad (3.6)$$

Otherwise;

$$V(M_1 \geq M_2) = \text{htg } M_1 \cap M_2 = \frac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)} \quad (3.7)$$

Both M_1 and M_2 values are needed to make the comparison given above.

The degree of possibility for a convex fuzzy number to be greater than k convex fuzzy numbers M_i ($i=1, 2, \dots, k$) can be defined by Eqn (8)

$$V(M \geq M_1, M_2, \dots, M_k) = V[(M \geq M_1)] \text{ and } (M \geq M_2) \text{ and } \dots \text{ and}$$

$$[(M \geq M_k)] = \min V(M \geq M_i); \quad (3.8)$$

$$i = 1, 2, 3, \dots, k$$

Assuming that, $d'(A_i) = \min V(S_i \geq S_k)$ for $i=1, 2, \dots, n; k \neq i$, the weigh vector (W) is calculated by using the following formula:

$$W' = (d'(A_1), (A_2), \dots, d'(A_n))^T \quad (3.9)$$

Where: A_i ($i = 1, 2, 3, \dots, n$) are n elements.

The last step is the normalization which is calculated using the equation given below:

$$W = (d(A_1), d(A_2), \dots, d(A_n))^T \quad (3.10)$$

Step 4. Calculating the fuzzy Eigen Value: After Chang's extent analysis was applied to the pairwise comparison matrices, the Eigen value of each matrix was calculated to check the consistency of these matrices. A consistency check is another strength of the AHP method that no other multi-criteria decision-making method can achieve. The consistency of each matrix is checked by using the consistency index (C.I.) and consistency ratio (C.R) as proposed by Saaty [60].

The consistency of a matrix is evaluated by using Eqns (11) and (12):

$$C.I. = \frac{\lambda_{max} - n}{n - 1}; \quad (3.11)$$

$$C.R = \frac{C.I.}{R.I.} \quad (3.12)$$

Where: λ_{max} is the largest Eigen value of the comparison matrix, n is the dimension of the matrix, and R. I. is the random consistency index of the matrix chosen from Table 3.5.

Table 3.5 RI of random matrices [122]

n	1	2	3	4	5	6	7	
RI	0	0	0.52	0.89	1.12	1.26	1.36	
n	8	9	10	11	12	13	14	15
RI	1.41	1.46	1.49	1.52	1.54	1.56	1.58	1.59

According to Saaty [60], the overall consistency ratio should be equal to or less than 10%. Otherwise, the answers of the experts are considered to be inconsistent [123]. In such a case, the decision-makers must check their answers.

Since in-house codes were written for this study, to avoid any coding errors, the computational accuracy was tested using the data presented by Chang [67], Işık and Aladağ [124]. This verification showed that the analysis conducted with coded MATLAB script gave the same results as these studies; therefore, the codes were determined as reliable. In addition, the consistency check feature was also added to the system, and all matrices were found consistent. The consistency ratios of the matrices were 0.0077, 0.0076 and 0.0071 for the pairwise comparisons of the main criteria, design-related characteristics, and the project management characteristics, respectively. It should be noted that consistency can be checked only when the matrix size is greater or equal to 3 [60]. Thus, there are no consistency measures for construction-related characteristics,

external-related characteristics, and project-management related characteristics. Finally, the weights of the project characteristics obtained as a result of fuzzy AHP analysis were given in Table 3.2.

3.2.3 Hybrid Similarity Measurement Method

The term “historical case” refers to construction projects stored in the database while a new construction project is called 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 3.2. 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 .

$$Sim_j(Z_0, Z_i) = \begin{cases} 1, & p_{ij} = p_{0j} \\ 0, & p_{ij} \neq p_{0j} \end{cases} \quad (3.13)$$

- 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:

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

$$\text{Where: } \Delta_j^{max} = \max \left\{ \sqrt{(p_{ij} - p_{0j})^2} \right\} \text{ and } \Delta(p_{ij}, p_{0j}) \in [0,1] \quad (3.14)$$

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 symmetry, reflexivity, and multiplicative transitivity [125], [126].

$$Sim_j(Z_0, Z_i) = \exp[-\Delta(p_{ij}, p_{0j})] \quad (3.15)$$

- 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 $p_{ij} = (p_{ij}^a, p_{ij}^b, p_{ij}^c)$ and $p_{0j} = (p_{0j}^a, p_{0j}^b, p_{0j}^c)$.

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

$$\text{Where: } \Delta_j^{max} = \max \left\{ \sqrt{(p_{ij}^a - p_{0j}^a)^2 + (p_{ij}^b - p_{0j}^b)^2 + (p_{ij}^c - p_{0j}^c)^2} \right\} \quad (3.16)$$

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

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

$$Sim_j(Z_0, Z_i) = \exp[-\Delta(p_{ij}, p_{0j})] \quad (3.17)$$

Finally, all local similarities calculated as indicated above are aggregated by using weights in Table 3.2. The following formula was used for this purpose:

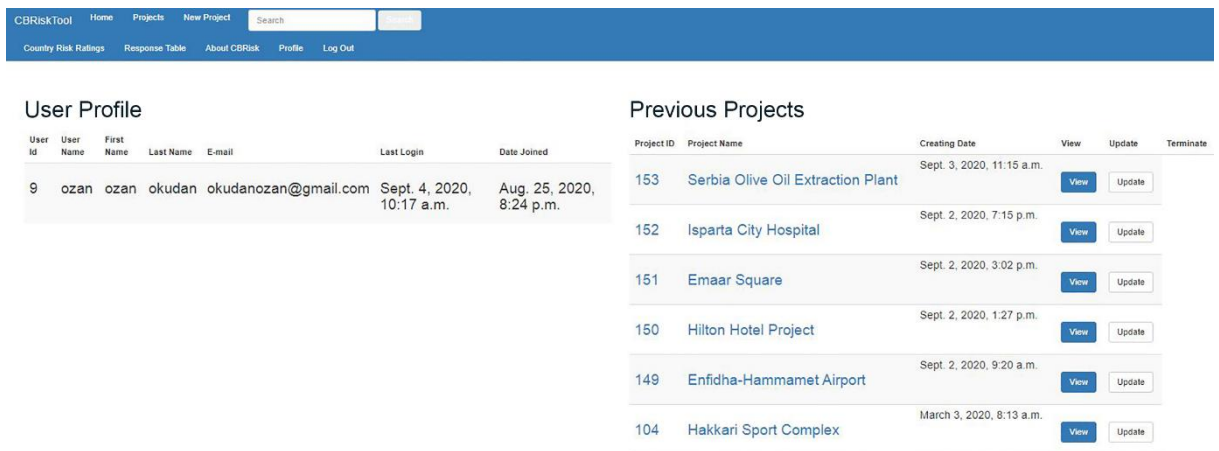
$$Sim(Z_0, Z_i) = \sum_j w_j * Sim_j(Z_0, Z_i) \quad (3.18)$$

3.3 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 3.8 and 3.9. 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 [4]. 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. [4] 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 3.3. 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 [4]. PMBOK [1] 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.



The screenshot displays the main interface of the CBRiskTool. At the top, there is a navigation bar with links for Home, Projects, and New Project, along with a search bar. Below the navigation bar, there are links for Country Risk Ratings, Response Table, About CBRisk, Profile, and Log Out. The main content area is divided into two sections: User Profile and Previous Projects.

User Profile

User Id	User Name	First Name	Last Name	E-mail	Last Login	Date Joined
9	ozan	ozan	okudan	okudanozan@gmail.com	Sept. 4, 2020, 10:17 a.m.	Aug. 25, 2020, 8:24 p.m.

Previous Projects

Project ID	Project Name	Creating Date	View	Update	Terminate
153	Serbia Olive Oil Extraction Plant	Sept. 3, 2020, 11:15 a.m.	View	Update	
152	Isparta City Hospital	Sept. 2, 2020, 7:15 p.m.	View	Update	
151	Emaar Square	Sept. 2, 2020, 3:02 p.m.	View	Update	
150	Hilton Hotel Project	Sept. 2, 2020, 1:27 p.m.	View	Update	
149	Enfidha-Hammamet Airport	Sept. 2, 2020, 9:20 a.m.	View	Update	
104	Hakkari Sport Complex	March 3, 2020, 8:13 a.m.	View	Update	

Figure 3.8 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/QC 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 L...	Design Department	Update
424	Unforeseen Ground Conditions	The total construction area of the project was 11 km ² . 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 Satec 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 3.9 A section of the final risk register belonging to an airport project

DISCUSSION OF THE FUZZY AHP RESULTS

Weights of project characteristics on the occurrence of risks were given in Table 3.2. These results indicate that each project characteristic has a different weight. This finding can support the hypothesis of this study, stating that the characteristics of a project have different effect levels on risk occurrence. Thus, the risk managers should consider the most effective project characteristics to identify the projects that are similar to their projects, and they should use previous experiences gained in these projects rather than relying solely on their judgments.

Based on the ranks of the project characteristics shown in Table 3.2, the most effective project characteristic on risk occurrence is determined as “contract-related characteristics” with a weight of 0.1058. Cevikbas and Koksall [121], [127] also asserted that contractual requirements embodied in the general conditions of contracts can be considered as potential sources of risks. In addition, Dikmen et al. [4] identified that the contract conditions are one of the important reasons for risks in construction projects. Similarly, Ustinovichius [128] stated that the specifications of contracts and their requirements have the potential to lead to risks. Therefore, this result came as no surprise since deficiencies in a contract subsequently can cause uncertainties throughout the project, which lead to risks [113]. In addition, one of the purposes of the contracts is to clarify the scope of the projects. In this context, the contracts should eliminate all ambiguities in the scope of the projects. However, when ambiguities about the project scope exist in the contract, more and more design changes will be confronted during the construction process, and thus cost and time overruns are inevitable due to the extensive reworks [111]. Consequently, it is evident that there is a direct relationship between the contract conditions and risk occurrence. Therefore, the similarity between the contract conditions should be considered during the process of determining similar projects that can be used to identify risks.

“Vagueness in contract clauses” obtained a higher score in the “contract-related characteristics” category compared to the “clarity of contract document” characteristic. Fidan et al. [70] highlighted the importance of “vagueness in contract clauses” with an

example obtained via a case study conducted in Dubai. They stated that due to the vagueness in the contract, the contractors were confronted with many difficulties, such as regular changes of the position of the crane and coordination problems. Even this example shows that any kind of vagueness in the contract leads to the occurrence of unexpected risks. In addition, the parties involved in a project can understand the clauses in different ways due to the vagueness [129], which may lead to the occurrence of risks as the responsibilities are not clearly assigned to the parties. Consequently, the similarities between the vagueness level in the contract clauses should be checked while identifying similar projects.

“Contract type” was rated as the second most important major project characteristic with a weight of 0.0962. The main reason for this finding can be that contract type is the term used to signify the differences in the contract structure or form, including compensation arrangements and especially risk allocation. For instance, Besaiso et al. [130] compared FIDIC and NEC in terms of risk management and allocation and concluded that these two contract types have different approaches and frameworks for risk management and allocation. Especially, risk allocation is an extremely important term since it indicates the amount of risk taken by either the client or the contractor [131]. Thus, the amount of risk taken by the company greatly varies with respect to the “contract type.” Consequently, the risk managers should consider the contract type for determining the similarities between the projects.

“Project value,” which can also be called contract value, is placed third in the order. This term might be considered as an important indicator of the complexity of a project, since high project value is often proportional to project complexity [132], and there is a direct relationship between the project complexity and complexity related risks [133]. In other words, construction companies take more risks when the complexity of a project increases. In addition, project complexity creates a network of interdependent risks [134]. In other words, an upstream risk can create numerous downstream risks; on the other side, several ‘upstream’ risks, which may belong to different categories, can lead to the emergence of a downstream risk [135]. In addition, project finance is another term associated with the project value, since companies must seek a sponsor to reach the required capital to carry out a project. This process, however, comes at a price. For instance, a company must be more careful about project’s cash flow and other financial

indicators to be able to pay all its liabilities. If not, project risks will eventually increase, and the project will become more vulnerable.

“Construction-related characteristics” obtained the fourth highest rank among the main criteria. The construction stage of a project involves numerous uncertainties. Therefore, it is usually associated with a high degree of risk due to the nature of the construction business activities, processes, environment, and organization [136]. Thus, these characteristics are some of the significant contributors to the risks of construction projects [137]. The complexity of the construction methods obtained a slightly higher score than the accessibility of the site. However, both characteristics could be considered equally important due to the similarity of their scores. The importance of innovative and advanced methods has been increasing with the increase in the number of complex projects. However, innovative solutions consist of more uncertainties, since the solutions have been implemented in a limited number of projects, in other words, the experience level of the companies for applying these solutions is low. Therefore, innovative solutions can be risky and create unanticipated effects [138], and innovation is also perceived to be correlated with risky decisions and doubtful results [139]. Especially, innovation creation is highly correlated with high risk [140]. In addition, innovative and advanced methods require special machinery, special equipment, and highly qualified workforces. The availability of these resources can also lead to different risks. On the other hand, the accessibility of a site can also be an issue. Routes of a construction site must be appropriately designed in a way that smooth delivery of materials, safe machine operation, and relatively easy relocation of large objects are possible on the site [141]. Site planning has a direct impact on cost and construction progress in the event of unforeseen conflict [142]. Especially in urban areas, accessibility to the construction site can create uncertainties and risks. Therefore, enough attention should be paid to “construction-related characteristics” in the risk identification stage.

Validation of the tool was carried out with a two-step procedure as shown in Figure 3.1. 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, the 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 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 Udejaja et al. [143] and Eken et

al. [31] 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 that 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. The process model shown in Figure 3.3 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 3.3 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 5.1 Answers of the participants to questionnaire survey

Survey Questions	Respondents				
	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 catalog 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

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. [46], 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 [1] 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.



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A

QUESTIONNAIRE SURVEY CONDUCTED TO DETERMINE WEIGHTS

This section is devoted to a questionnaire survey conducted to determine the weights of project features.

Please evaluate the importance of each project feature from the perspective of risk management. Each cell should be inserted degree of importance and an arrow showing the direction of the importance. While carrying out evaluation, linguistic variables should be used to indicate degree of importance. These variables are provided in Table 3.4.													
	← ↑	PT	C	DS	PV	D	TCA	CT	DR	CR1	ER	PR	CR2
PT	Project type	JE											
C	Country		JE										
DS	Delivery system			JE									
PV	Project value				JE								
D	Duration					JE							
TCA	Total construction area						JE						
CT	Contract type							JE					
DR	Design-related features								JE				
CR1	Construction-related features									JE			
ER	External-conditions related features										JE		
PR	Project management-related features											JE	
CR2	Contract-related issues												JE

Note: JE stands for Just Equal

Table A.1 Evaluation of the main project features

Table A.2 Evaluation of design-related project features

Please evaluate each project feature in a similar manner described in Table A.1.				
	The complexity of the design	The completion level of design	Constructability level	Quality of design
The complexity of the design	JE			
The completion level of design		JE		
Constructability level			JE	
Quality of design				JE

Table A.3 Evaluation of construction-related project features

Please evaluate each project feature in a similar manner described in Table A.1.		
	The complexity of construction methods	Accessibility of the site
The complexity of construction methods	JE	
Accessibility of the site		JE

Table A.4 Evaluation of external-related project features

Please evaluate each project feature in a similar manner described in Table A.1.		
↑ ←	The comprehensiveness of geotechnical investigation	Climate & weather conditions
The comprehensiveness of geotechnical investigation	JE	
Climate & weather conditions		JE

Table A.5 Evaluation of project management-related project features

Please evaluate each project feature in a similar manner described in Table A.1.				
↑ ←	The strictness of quality management requirements	The strictness of environmental management	The strictness of safety management requirements	The strictness of project management requirements
The strictness of quality management requirements	JE			
The strictness of environmental management		JE		
The strictness of safety management requirements			JE	
The strictness of project management requirements				JE

Table A.6 Evaluation of contract-related project features

Please evaluate each project feature in a similar manner described in Table A.1.		
↑ ←	Vagueness in contract clauses	Clarity of contract documents
Vagueness in contract clauses	JE	
Clarity of contract documents		JE

B

SOFTWARE ARCHITECTURE OF FUZZY AHP SCRIPT

In this section, the methodology followed by the script, and the architecture of the software will be presented. The script was designed as a console system, therefore the users should have basic Matlab knowledge. The script has three modules named consistency, fuzzification, and fuzzy AHP. When the code is run, a dialogue box appears on the screen and the user enters which module he or she wants to use. Then, only the specific module stated by the user runs.

Consistency Ratio Module

This module of the script calculates the consistency of the pairwise comparison matrix prepared by the experts. To calculate the consistency, firstly all matrices should be imported as a variable to the workplace of the Matlab. When the consistency module is operated, it is asked from the user to insert the number of the matrices that are desired to check. Then, the name of each matrix (or variable) is entered by the user and the system creates variable “report” and summarizes the consistencies of all matrices.

The methodology proposed by Saaty [60] was adopted and the steps of the calculation are as follows.

The C.I of a matrix are calculated by using Eqns (1) and (2):

$$C.I. = \frac{\lambda_{max} - n}{n - 1}; \quad (B.1)$$

$$C.R = \frac{C.I.}{R.I.} \quad (B.2)$$

Where: λ_{max} is the largest Eigenvalue of the comparison matrix, n is the dimension of the matrix, and R. I. is the random consistency index of the matrix chosen from Table 3.5.

The codes of the consistency module are given in Table B.1.

Table B.1 The codes of consistency ratio module.

The codes of the module
<pre> switch func case 'c' %Consistency index r=inputdlg('Please insert the number of matrices to be checked'); r=cell2mat(r); r=str2num(r); RItable=[0 0 0.58 0.9 1.12 1.24 1.32 1.41 1.45 1.49 1.52 1.54 1.56 1.58 1.59]; for x=1:r variable=inputdlg('Please insert the name of the variable'); variable=string(variable); [~, a]=size(evalin('base',variable)); eigenmax=max(eig(evalin('base',variable))); CI=(eigenmax-a)/(a-1); RI=RItable(1,a); CR=CI/RI; Report(x,1)=CR; end warndlg('Check variable "Report"') </pre>

Fuzzification Module

Fuzzification is the first step of the fuzzy AHP analysis. The respondents prepare the pairwise comparison matrices by using linguistic variables. Then, linguistic variables have to be converted to the 1-6 scale and the new matrix should be inserted into the script. The script re-arranges the matrix by using fuzzy numbers. In other words, the script fuzzifies the matrix. As a final step, the script saves the new matrix under the specific name entered by the user. It should be noted that each matrix should be inserted into the system individually. The system completes the fuzzification process by using the triangular fuzzy scale shown in Table 3.4. The codes of the fuzzification module are shown in Table B.2.

Table B.2 The codes of the fuzzification module

The first section of the code	The second section of the code
<pre> case 'f' warndlg('Name of the variable should be "Decisionmaker"') [~, r]=size(Decisionmaker); fuzz=[1 1 1]; for x=1:r z=1; for y=1:r if Decisionmaker(x,y)==1 fuzz(x,z)=1; z=z+1; fuzz(x,z)=1; z=z+1; fuzz(x,z)=1; z=z+1; elseif Decisionmaker(x,y)==2 fuzz(x,z)=0.5; z=z+1; fuzz(x,z)=1; z=z+1; fuzz(x,z)=1.5; z=z+1; elseif Decisionmaker(x,y)==3 fuzz(x,z)=1; z=z+1; fuzz(x,z)=1.5; z=z+1; fuzz(x,z)=2; z=z+1; elseif Decisionmaker(x,y)==4 fuzz(x,z)=1.5; z=z+1; fuzz(x,z)=2; z=z+1; fuzz(x,z)=2.5; z=z+1; elseif Decisionmaker(x,y)==5 fuzz(x,z)=2; z=z+1; fuzz(x,z)=2.5; </pre>	<pre> elseif Decisionmaker(x,y)==0.5 fuzz(x,z)=0.66; z=z+1; fuzz(x,z)=1; z=z+1; fuzz(x,z)=2; z=z+1; elseif Decisionmaker(x,y)==1/3 fuzz(x,z)=0.5; z=z+1; fuzz(x,z)=0.66; z=z+1; fuzz(x,z)=1; z=z+1; elseif Decisionmaker(x,y)==1/4 fuzz(x,z)=0.4; z=z+1; fuzz(x,z)=0.5; z=z+1; fuzz(x,z)=0.66; z=z+1; elseif Decisionmaker(x,y)==1/5 fuzz(x,z)=0.33; z=z+1; fuzz(x,z)=0.4; z=z+1; fuzz(x,z)=0.5; z=z+1; elseif Decisionmaker(x,y)==1/6 fuzz(x,z)=0.285; z=z+1; fuzz(x,z)=0.33; z=z+1; fuzz(x,z)=0.4; z=z+1; end end end name=inputdlg('Insert the ID of the decisionmaker that you want to save','s'); </pre>

Fuzzy AHP Module

This is the last module of the system. To operate this module, firstly all fuzzified matrices of the decision-makers should be imported to the workspace. However, this module requires a specific naming convention for the analysis. For instance, the matrix of the first decision-maker should be named DM1 and the others should be named DM2, DM3,

and DMX respectively. The system aggregates all of the matrices by using the geometric mean [62]. Then, the fuzzy AHP analysis starts.

Chang's extent analysis method was followed in the development of this script. This method was used to find the weights of each criterion. Chang's [67] extent analysis provides a general method of using crisp mathematical concepts to address fuzzy quantities. The codes of the system are given in Table B.3.

Table B.3 The codes of the fuzzy AHP module

The Codes of the module
<pre> %Aggregationofdecisionmatrix %load all the variables case 'fa' num=inputdlg('Insert the number of respondents'); num=cell2mat(num); num=str2num(num); %Enter the name of each variable below. Decisionmatrix=(DM1.*DM2.*DM3.*DM4.*DM5.*DM6.*DM7.*DM8.*DM9.*DM10.*DM11.*DM 12.*DM13.*DM14.*DM15).^(1/num); %Calculation OF S_value [r, c]=size(Decisionmatrix); y=1; totaltotal_l=(1); totaltotal_m=(1); totaltotal_u=(1); total_l=(1); total_m=(1); total_u=(1); for x=1:r total_l(1,x)=sum(Decisionmatrix(:,y)); y=y+3; end totaltotal_l=sum(total_l); total_Mg_l=(1); y=2; for x=1:r total_m(1,x)=sum(Decisionmatrix(:,y)); y=y+3; end totaltotal_m=sum(total_m); y=3; for x=1:r total_u(1,x)=sum(Decisionmatrix(:,y)); y=y+3; end totaltotal_u=sum(total_u); %total_Mg Values for z=1:r y=1; total_Mg_l(z,1)=0; for x=1:r </pre>

Table B.3 The codes of the fuzzy AHP module (continued)

The Codes of the module
<pre>total_Mg_l(z,1)=total_Mg_l(z,1)+Decisionmatrix(z,y); y=y+3; end end total_Mg_m=(1); for z=1:r y=2; total_Mg_m(z,1)=0; for x=1:r total_Mg_m(z,1)=total_Mg_m(z,1)+Decisionmatrix(z,y); y=y+3; end end total_Mg_u=(1); for z=1:r y=3; total_Mg_u(z,1)=0; for x=1:r total_Mg_u(z,1)=total_Mg_u(z,1)+Decisionmatrix(z,y); y=y+3; end end %Synthetic Values total_Mg=[total_Mg_l total_Mg_m total_Mg_u]; Svalues=[total_Mg_l/totaltotal_u total_Mg_m/totaltotal_m total_Mg_u/totaltotal_l]; d=(1); for y=1:r for x=1:r if Svalues(y,2) >= Svalues(x,2) d(y,x)=1; else d(y,x)=(Svalues(x,1)-Svalues(y,3))/((Svalues(y,2)-Svalues(y,3))-(Svalues(x,2)-Svalues(x,1))); end end end Weights=(1); for x=1:r Weights(x,1)=min(d(x,:)); end Sumall=sum(Weights); Normalized=Weights/Sumall; warndlg('Check variable "Normalized"') end</pre>

PUBLICATIONS FROM THE THESIS

Papers

1. O. Okudan, C. Budayan, and I. Dikmen, "A knowledge-based risk management tool for construction projects using case-based reasoning," *Expert Syst. Appl.*, vol. 173, p. 114776, Jul. 2021, doi: 10.1016/j.eswa.2021.114776.
2. O. Okudan and C. Budayan, "Assessment of project characteristics affecting risk occurrences in construction projects using fuzzy AHP," *Sigma J. Eng. Nat. Science*, vol. 38, no. 3, pp. 1447–1462, 2020.

Conference Papers

1. Okudan and C. Budayan, "Matlab Script for Fuzzy AHP Analysis", in *6th international Project and Construction Management Conference*, Istanbul, Turkey, 12-14 November 2020, vol. 6, pp. 1377-1385.

Projects

1. A Knowledge-based risk management tool for construction projects using case-based reasoning, Assoc. Prof. Dr. Cenk BUDAYAN, 06.01.2020 - 06.07.2021, Researcher.