

# *A knowledge-based risk management tool for construction projects using case-based reasoning*

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

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10 ***Abstract***

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

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

## 30 **1. Introduction**

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

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

46 RM is a knowledge-intensive process since RM generates a high amount of knowledge and  
47 utilizes this knowledge (Yildiz, Dikmen, Birgonul, Ercoskun, & Alten, 2014). PMBOK (2018)  
48 also underlines the importance of knowledge stemming from an individual's experience for  
49 RM. In this respect, knowledge-based RM has been advocated by many researchers to improve  
50 the effectiveness of companies' RM practices. Dikmen et al. (2008) used the term "learning  
51 from risk" to suggest "a knowledge-driven risk management process" and "focus on lessons  
52 learned" for better RM. Learning from risk necessitates creating, securing, capturing,  
53 coordinating, combining, retrieving, and disseminating the risk-related knowledge of the  
54 projects (H. P. Tserng & Lin, 2005). In practice, RM in the construction projects depends on  
55 tacit knowledge that is generally stored in the minds of individuals rather than corporate risk  
56 memory, which in turn may lead to loss of critical knowledge due to the high staff turnover in  
57 the industry. Therefore, effective exploitation of risk-related knowledge stored in corporate risk  
58 memory, such as lessons learned from previous projects about risk events, consequences,

59 effectiveness of response strategies etc. is of vital importance. Corporate risk memory allows  
60 companies to update their risk management knowledge and eventually they may have precise  
61 and accurate forecasts about risks, likelihood of risk occurrence, as well as their consequences  
62 (Dikmen et al., 2008). Atkinson et al. (2006) also pinpointed that risk-related experience gained  
63 throughout the past projects is the fundamental necessity for accurate risk estimations. Although  
64 each project is a unique and temporary undertaking, they still have similar features such as the  
65 structure of teams, construction processes, tools/methods, and skills (Kamara, Anumba,  
66 Carrillo, & Bouchlaghem, 2003). Due to these similarities, the same problems seen in one  
67 project are likely to re-occur in forthcoming projects until an appropriate solution is  
68 implemented (Eken, Bilgin, Dikmen, & Birgonul, 2015). Consequently, the companies can  
69 perform more effective RM in forthcoming projects by constructing and utilising a corporate  
70 risk memory. In this way, it is ensured that the re-invention of the wheel at every project would  
71 be prevented. However, capturing risk knowledge during the past and/or current projects, and  
72 exploiting this knowledge during the life cycle of a current and/or forthcoming project is a  
73 challenging task for most construction companies (Kivrak, Arslan, Dikmen, & Birgonul, 2008).  
74 Many researchers argued that construction companies can barely capture, store, and disseminate  
75 knowledge to optimize the RM of forthcoming projects (Alashwal & Abdul-Rahman, 2014;  
76 Fong, 2005). Although the benefits of knowledge-based systematic RM are widely discussed  
77 in the literature (Abu Bakar, Yusof, Tufail, & Virgiyanti, 2016; Chan, Cooper, &  
78 Tzortzopoulos, 2005; Vakola & Rezgui, 2000; Yang et al., 2014), implementation of these  
79 systems in practice is rather low among the construction companies due to the lack of learning  
80 culture and ineffective knowledge management (KM) processes/tools (Ford, Voyer, &  
81 Wilkinson, 2000; Kivrak et al., 2008; McLaughlin, Paton, & Macbeth, 2008; Steiner, 1998; Tan  
82 et al., 2010). In literature, efforts have been devoted by several authors to establish systematic  
83 knowledge-based RM tools such as Dikmen et al. (2008), Yildiz et al. (2014), and Fan et al.  
84 (2015). However, each tool or approach has its own assumptions and methodological  
85 drawbacks.

86 This study, therefore, aims to develop a web-based organizational learning tool that can be used  
87 for capturing, storing, retrieving, and disseminating risk-related knowledge. The tool has been  
88 designed to support all processes of RM and facilitate knowledge-based RM. In this study, as  
89 an artificial intelligent method, Case-based reasoning (CBR) has been used to develop the tool.  
90 CBR has been identified as an ideal and promising method to exploit risk-related knowledge

91 from past projects (Lu, Li, & Xiao, 2013). The web-based tool, named “CBRisk”, has the  
92 potential to be used by construction organizations to develop a corporate risk memory that can  
93 store risk-related knowledge of construction projects and aid decision-makers for risk  
94 identification, risk analysis, and risk response steps in new projects by retrieving the risk-related  
95 knowledge of similar previous projects.

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

112

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

## 121 2. Research Background and Motivation

### 122 2.1. Knowledge management in construction

123 Davenport and Prusak (1998) define knowledge as “a fluid mix of framed experience, values,  
124 contextual information, and expert insight”. As construction projects have become more  
125 complex and challenging in recent years, knowledge has become a critical resource for  
126 construction companies. Knowledge as a source of competitive advantage has been widely  
127 mentioned in the literature (Eisenhardt & Martin, 2000; Kivrak et al., 2008). To exploit the  
128 benefits of knowledge, an appropriate mechanism is needed to capture and disseminate it  
129 (Kivrak et al., 2008). Although many efforts have been devoted to the development of effective  
130 KM mechanisms in the construction management literature, this research area is not mature and  
131 there is still some distance to be covered (Eken, Bilgin, Dikmen, & Birgonul, 2020; Tan et al.,  
132 2010). Studies on the development of KM mechanisms to improve RM are even more limited  
133 (Dikmen, Birgonul, Tah, & Ozer, 2012; Yildiz et al., 2014). Although it has been widely  
134 discussed by researchers that risk-related knowledge of the companies must be embedded in a  
135 non-human repository such as routines, databases, or structures (Eken et al., 2020; King, Chung,  
136 & Haney, 2008; Öztürk, Arditi, Günaydın, & Yitmen, 2016), construction professionals usually  
137 use their subjective judgement for risk-informed decision-making and lack a formalised process  
138 for knowledge-based RM.

139 Some strategies can be implemented to manage knowledge effectively within a company. These  
140 strategies can be categorized as “techniques” and “technologies” (Eken et al., 2020).  
141 Techniques are defined as non-information Technology (IT) tools while technologies are IT-  
142 tools that require the development of a system to manage the knowledge with the help of  
143 information technologies (Al-Ghassani, Anumba, Carrillo, & Robinson, 2005). Technologies  
144 can provide fertile ground for articulating, storing, and sharing knowledge (Alavi & Denford,  
145 2015; Hayes, 2015). In the construction management literature, several IT-based tools have  
146 been developed to systematize KM within construction companies (Arditi, Polat, & Akin, 2010;  
147 Eken et al., 2020; Kim & Chi, 2019; Kivrak et al., 2008; Oti, Tah, & Abanda, 2018; Soibelman  
148 et al., 2003). However, majority of these tools are generic knowledge management tools, and  
149 usually do not offer a special technological solution to support the RM process. As these tools  
150 embody all types of knowledge related to construction techniques, stakeholders, suppliers, and  
151 RM, it may not be practical to exploit, and re-use risk-related knowledge from the huge

152 database. Consequently, technological solutions specifically developed to support RM should  
153 be developed and integrated with the KM system.

## 154 **2.2. CBR as a technique to develop knowledge-based systems in construction**

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

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

173 Owing to its above-mentioned benefits, CBR has drawn the attention of many researchers in  
174 the project and construction management domain. Bartsch-Spörl et al. (1999) surveyed both the  
175 scientific and practical applications of CBR. The study showed that CBR will have promising  
176 future, particularly in new areas like self-service and e-commerce applications. Considering the  
177 importance of tacit knowledge in the project-based industries, Noh et al. (2000) proposed a  
178 cognitive map (CM) to formalize the tacit knowledge and CBR based tool to store and retrieve  
179 it. Goh and Chua (2010) utilised a CBR-based approach to construction safety hazard  
180 identification. Behbahani et al. (2012) used CBR to develop a knowledge-based system for  
181 statistical process control where they developed a new format for representing cases and  
182 similarity measures for case retrieval. Hu et al. (2016) conducted a comprehensive literature



183 review of CBR applications in construction management studies considering the articles  
184 published between 1996 and 2015. The result of the study indicated that the popularity of CBR  
185 applications in construction management literature is increasing due to the similar mind-sets of  
186 CBR and problem-solving practices in the construction industry. Most recently, there have been  
187 studies on safety risk assessment and management in construction projects such as the work of  
188 Preira (2018) and Ayhan and Tokdemir (2019). Zhao et al. (2019) implemented CBR to support  
189 green retrofit decisions. Thus, considering its advantages and success of similar applications in  
190 the construction management domain, CBR appears as a promising method for knowledge-  
191 based risk management.

### 192 **3. The research questions**

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

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

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

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

### 203 **4.1. Critical review of knowledge-based RM tools developed for construction projects**

204 An extensive review of KM and RM literature revealed that knowledge-based RM tools should  
205 be equipped with several critical features to meet the needs of construction practitioners. Firstly,  
206 as elaborated above, RM is a systematic process that involves the identification of sources of  
207 uncertainty (risk identification), estimating the probability and impact of uncertain  
208 events/conditions on a project (risk analysis), generating response strategies, and finally,  
209 monitoring the risks (PMI, 2018; J.H.M Tah & Carr, 2001), therefore, an ideal knowledge-  
210 based RM tool should support all of these steps to effectively manage the risks of construction  
211 projects. Otherwise, the information provided by the tool could be incomplete and impractical  
212 to use in engineering practices. Besides, a significant part of the risk-related knowledge in the

213 construction projects is the tacit knowledge which is extremely rooted in individuals' minds  
214 and experiences (Eken et al., 2015; Kivrak et al., 2008; Ozorhon, Dikmen, & Birgonul, 2005),  
215 therefore a knowledge-based RM tool should be able to capture and formalize the tacit  
216 knowledge throughout the whole life cycle of the project. One of the most effective methods  
217 for tacit knowledge is live capturing of the risk-related knowledge and storing them in a  
218 corporate risk memory. Whereas, in the construction projects, a widely used knowledge  
219 capturing method, namely post-project evaluations, can be ineffective for capturing the tacit  
220 knowledge as some information might be lost during the project (Ly, Anumba, & Carrillo,  
221 2005). A knowledge-based RM tool should support live risk knowledge capture. In this respect,  
222 web-based platforms can be a convenient solution for the development of knowledge-based RM  
223 tools, since they enable live knowledge capture without time and location restriction (Aziz,  
224 Anumba, Ruikar, Carrillo, & Bouchlaghem, 2006; Han, Kim, Kim, & Jang, 2008; Lam & Ng,  
225 2006). Besides, the employees can access the web-based platforms anywhere in the world,  
226 anytime, with any device so that risk-related knowledge can be captured and reused effectively  
227 (Han et al., 2008). Another important feature that a knowledge-based RM should have is  
228 achieving inter-project learning which refers to the transfer of the knowledge and experience  
229 from one project to others, either within the same timeframe or over a period of time (Gieskes  
230 & ten Broeke, 2000). Considering that organizations can develop new knowledge by combining  
231 and sharing lessons-learned across projects (Kotnour & Kurstedt, 2000), inter-project learning  
232 becomes a vital concept for knowledge-based RM. Additionally, knowledge-based RM tools  
233 should be equipped with a case retrieval mechanism that can retrieve risk-related knowledge of  
234 similar projects. Because similar risks tend to re-occur in similar projects, and the decision-  
235 makers can use post-project risk event histories to give more reliable decisions (Dikmen et al.,  
236 2008; Okudan & Budayan, 2020). Finally, as Eken et al. (2020) underlined the importance of  
237 the quality of the captured knowledge for the reliability of knowledge management systems, a  
238 knowledge-based RM system should facilitate collaboration between different parties for  
239 capturing knowledge. The same study also stated that the system quality should be maintained  
240 by editing, deleting, and modifying the lessons and thus, knowledge-based RM system should  
241 also have a mechanism that makes possible it to review and check risk-related knowledge to  
242 ensure the reliability of the system. All these features are believed to improve the effectiveness  
243 of knowledge-based RM.

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

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

Reference	Brief description	Pros	Cons						
			A	B	C	D	E	F	
Tah and Carr (2001)	The first software prototype that can facilitate knowledge-based RM	<ul style="list-style-type: none"> <li>• Supports a knowledge-based RM process</li> <li>• Introduces a common language for describing risks and remedial measures.</li> </ul>		X	X	X	X	X	X
Zoysa and Russell (2003)	A knowledge-based risk identification system in large infrastructure projects	<ul style="list-style-type: none"> <li>• Capable of improving responsiveness of existing knowledge-based approaches to project attributes</li> </ul>		X	X	X	X	X	X
Choi et al. (2004)	A risk analysis software that is built upon an uncertainty model based on fuzzy concept	<ul style="list-style-type: none"> <li>• Capable of considering the degree of uncertainties involved in both probabilistic parameter estimates and subjective judgements</li> </ul>		X	X	X	X	X	X
Han et al. (2008)	A web-based decision support system for RM that can satisfy the specific needs of the construction practitioners	<ul style="list-style-type: none"> <li>• Supports project managers in key areas such as bid decision, profit prediction etc.</li> <li>• Has web-based architecture which eases the accessibility</li> </ul>	X	X		X	X	X	
Dikmen et al. (2008)	A computer-based RM tool that can facilitate knowledge-based RM	<ul style="list-style-type: none"> <li>• Capable of establishing lessons learned database and facilitating risk assessment throughout the project's life cycle</li> </ul>		X	X	X	X		
Tserng et al. (2009)	An ontology-based risk management framework to enhance the RM performance by improving the RM workflow and knowledge reuse	<ul style="list-style-type: none"> <li>• Capable of facilitating the identification, analysis, and response of project risks</li> </ul>		X	X	X	X	X	X
Cardenas et al. (2013)	An approach to capture and integrate risk-related knowledge to support RM of construction projects	<ul style="list-style-type: none"> <li>• Capable of identifying top risks in tunnel works</li> </ul>	X	X	X	X	X	X	X
Serpella et al. (2014)	A methodology based on a three-fold arrangement that includes modelling of the risk management function, its evaluation, and the availability of a best practices model	<ul style="list-style-type: none"> <li>• Allows clients and contractors to develop a project's risk management function based on best practices</li> </ul>	X	X	X	X	X	X	X
Yildiz et al. (2014)	A knowledge-based risk mapping tool for systematically assessing risk-related variables	<ul style="list-style-type: none"> <li>• Supports decision-making at the bidding and contingency estimation phase</li> </ul>	X	X	X	X	X	X	X

		<ul style="list-style-type: none"> <li>Introduces a novel methodology to estimate potential risk paths based on previous projects' knowledge</li> </ul>							
Ding et al. (2016)	An ontology-based tool for construction risk knowledge management in BIM environment	<ul style="list-style-type: none"> <li>Capable of linking the applicable knowledge to the specific objects in the BIM</li> </ul>	X	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.

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

255 **4.2.Critical review of CBR-based RM support tools and models**

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

274 The accuracy of case retrieval relies on the comprehensiveness of case representation and the  
 275 accuracy of the similarity measurement method. The case representation is the process of

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

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

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

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

Reference	Brief description	Pros	Cons		
			A	B	C

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

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

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

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

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

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

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

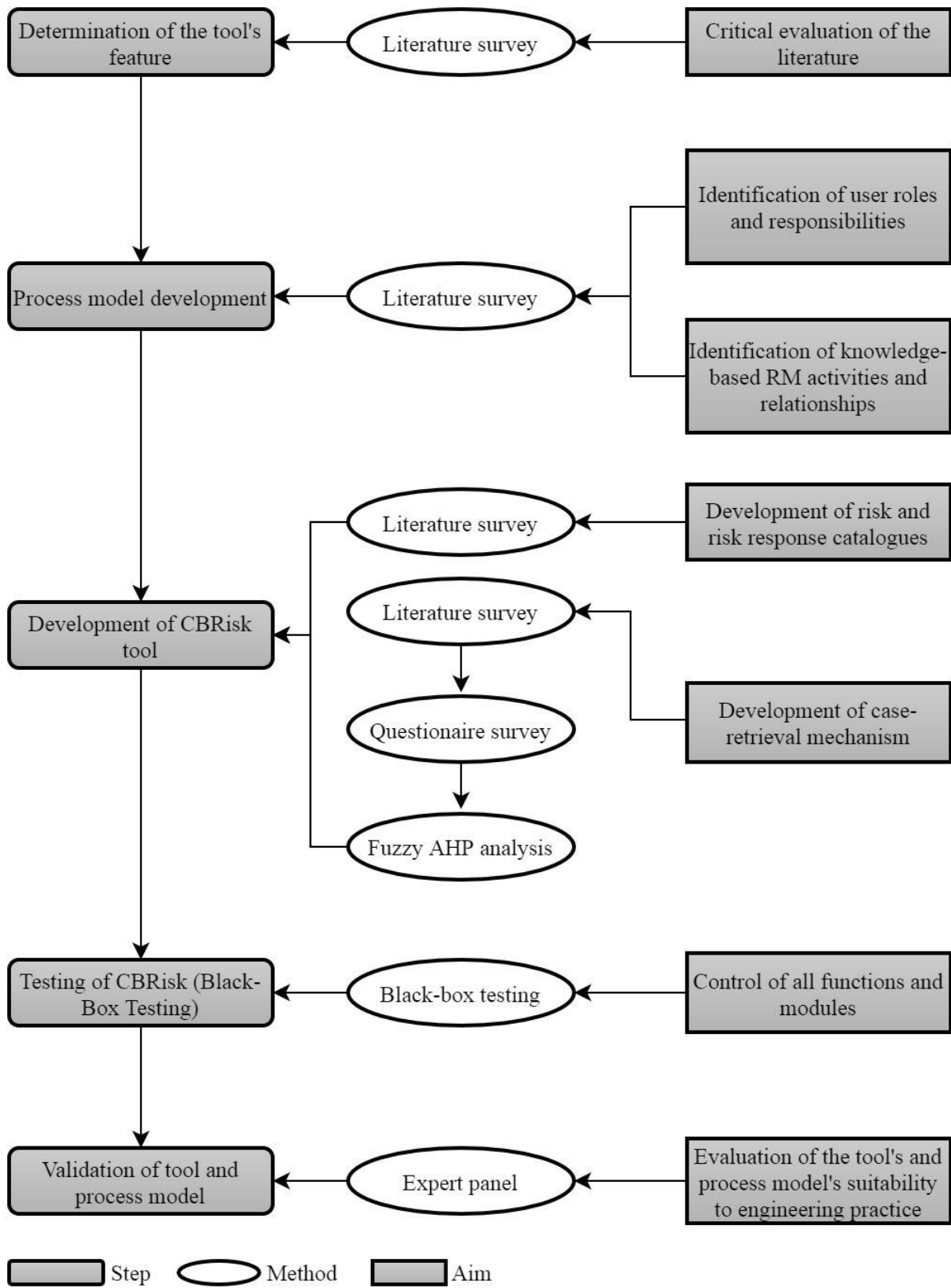
343 types of construction projects within their portfolio and learning from different project  
344 types is also possible. Thus, it was hypothesized that a knowledge-based RM tool that  
345 supports all project types would be useful.

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

## 349 **6. Research Methodology**

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





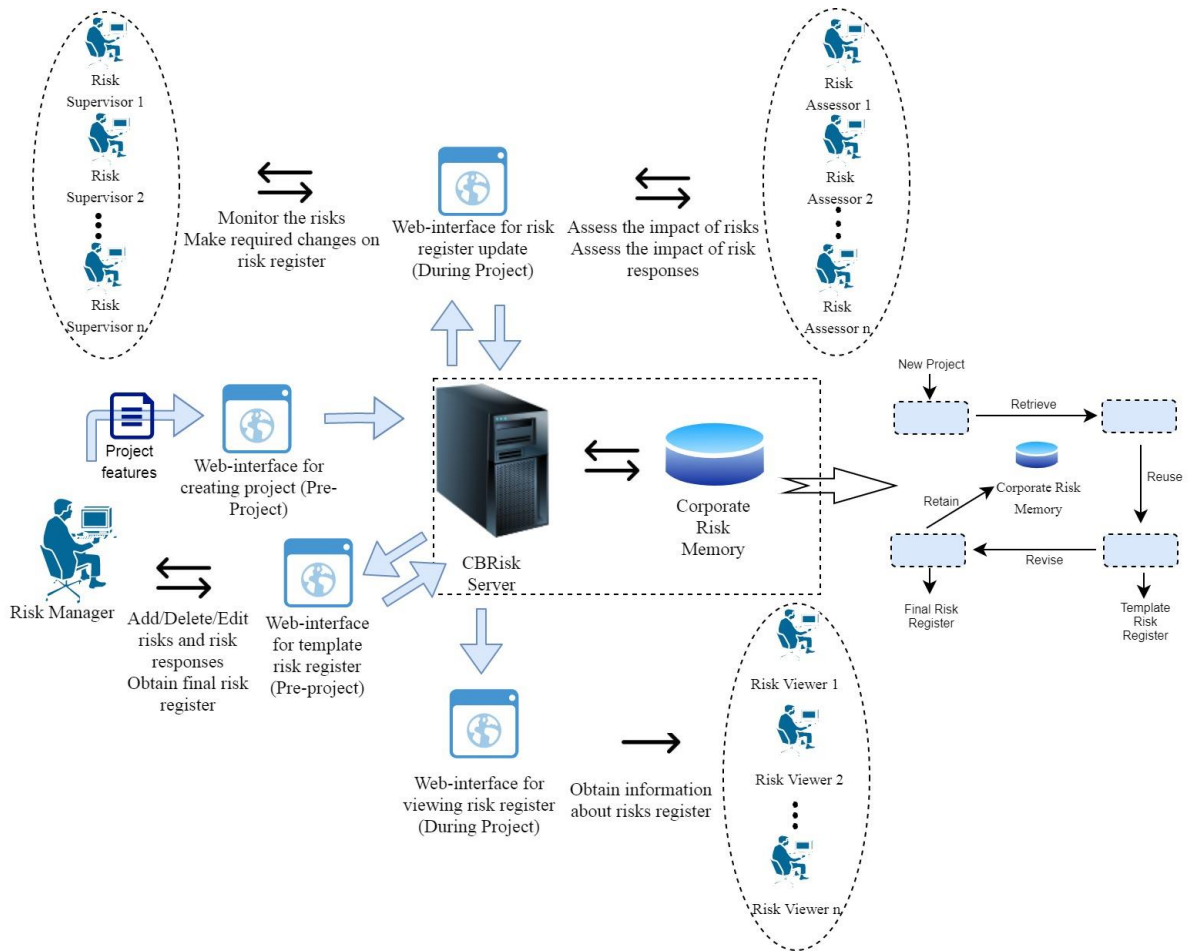
361 **Figure 1. Research Methodology**

362        **6.1. Software architecture**

363        **6.1.1. Overview of the tool**

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

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



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**Figure 2.** Structure of knowledge-based RM

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### 6.1.2. Knowledge-based RM activities throughout project life cycle

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Figure 3 is the process model and shows the knowledge-based RM activities to be performed with the aid of the tool. As stated above, this tool embraces all RM processes and aids the project team from the pre-project stage to the post-project stage. The first process of the RM is the identification of the risks at the pre-project stage. Accurate and comprehensible risk identification is a crucial process of RM (Wang, Dulaimi, & Aguria, 2004). Because subsequent processes are constructed upon the identified risks. Additionally, risk identification is critical for the bidding phase since unpredicted risks can increase the cost and duration of the project enormously. The tool offers an innovative and systematic solution to risk identification. As shown in Figure 3, the CBR system starts working in the background after the new project is created by inserting its specific features such as duration, project value, etc. Then, the CBR system retrieves the most similar projects from the database and merges risks of these similar past projects. Given the fact that similar risks tend to re-occur in similar projects, these risks

399 are expected to occur in this new project. Decision-makers were also assisted during the risk  
400 analysis process. The tool calculates the probability and impact of each risk identified in the  
401 previous process by following the methodology as explained in Section 3.3. The third RM  
402 management process performed at the pre-project stage is generating a response plan for each  
403 risk. The tool also guides decision-makers when it comes to generating a response plan to each  
404 risk. The tool lists previously performed risk responses and, their impact on time and cost from  
405 the previous projects for each risk. Thus, decision-makers can display which responses were  
406 taken against each risk in these similar past projects. Since the system retrieves response plans  
407 of only similar project's risks, these responses could also be implemented in this new project.  
408 In short, the software provides a template risk register based on similar past projects stored in  
409 the database.

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

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

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

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

442 **6.1.3. User roles and responsibilities**

443 The quality of the knowledge captured and saved in the database is a crucial factor for the  
 444 reliability of the tool. Because the CBR uses its database to identify risks, risk responses, etc.  
 445 Each irrelevant knowledge saved into the database can potentially affect the reliability of the  
 446 system. Thus, different types of roles and responsibilities are required to implement the  
 447 structure as given in Figure 2. Authorities such as creating projects, adding/deleting risks and

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

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

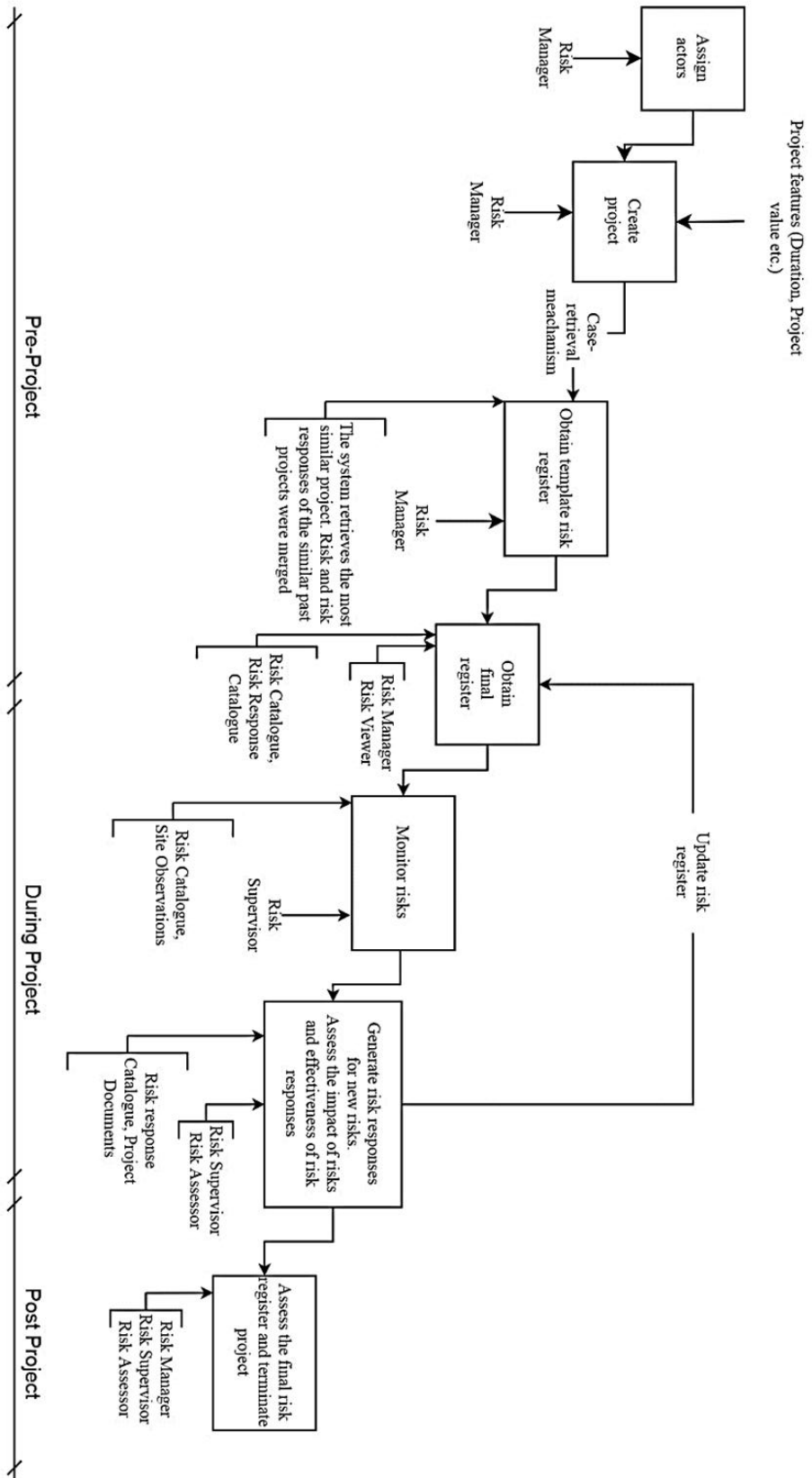
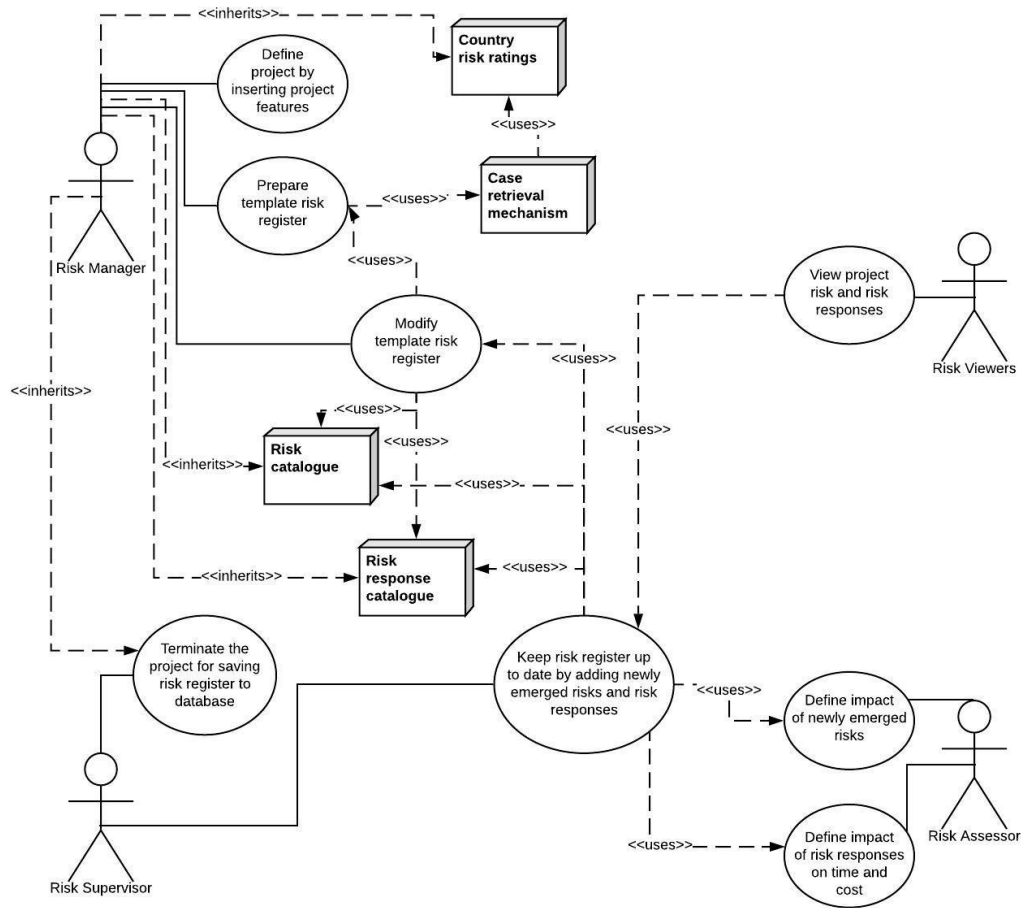


Figure 3. Process Model





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**Figure 4.** Use case diagram

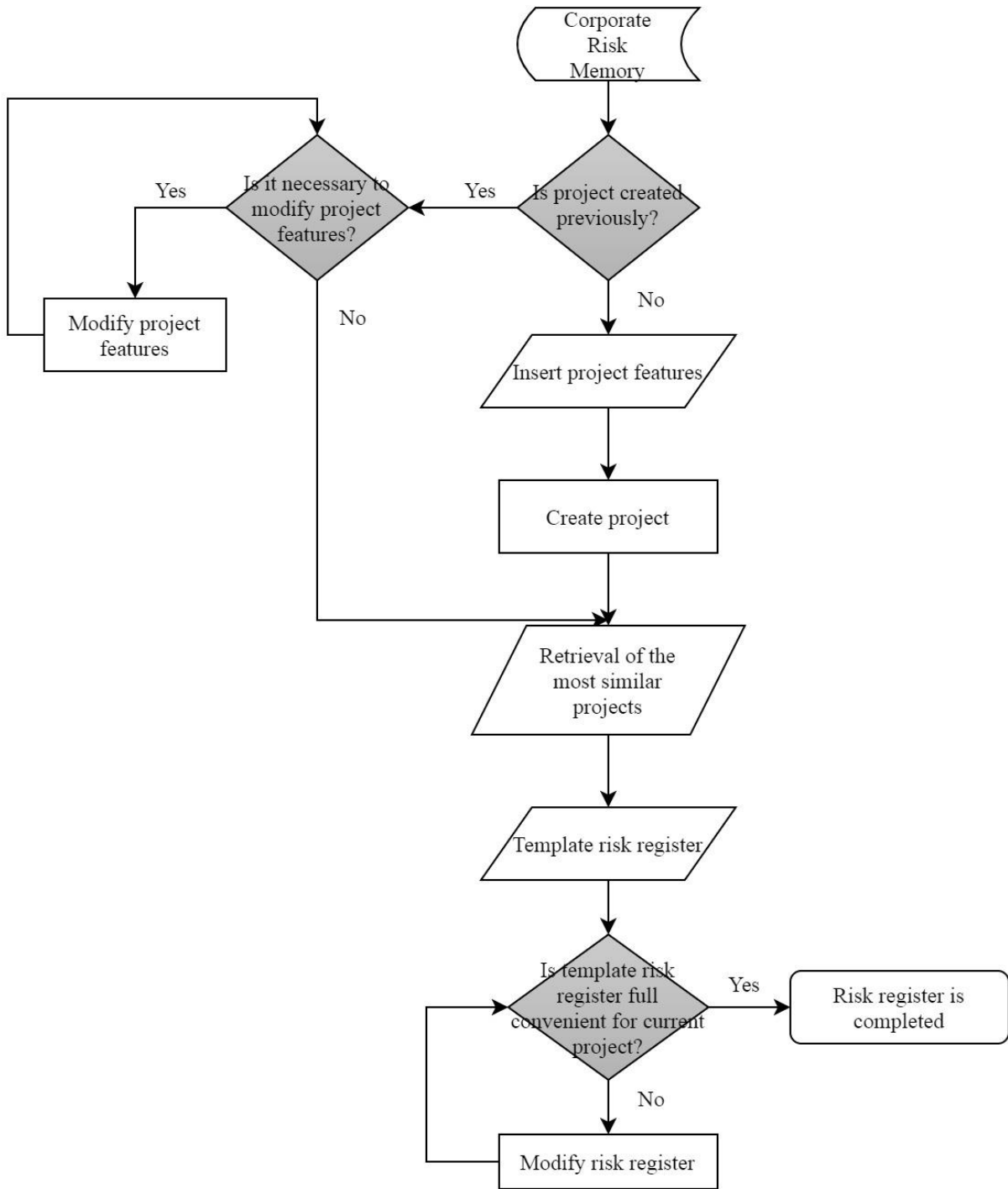
496 There are primarily two workflows within the system. The first one is creating a risk register at  
 497 the pre-project stage. This risk register is indispensable to calculate risk-adjusted cost and  
 498 duration so that potential cost and time overruns could be avoided (Dikmen et al., 2012). The  
 499 detailed procedure for this task is presented in Figure 5. Firstly, the project has to be created to  
 500 initiate the process. “Risk manager” has to enter various features related to a project that he/she  
 501 wants to create. These features are shown in Table 4 and they are employed to measure the  
 502 similarity between the current project and each project stored in the database. Determination of  
 503 project features and their normalized weights in Table 4 are elaborated at Sections 4.2.1 and  
 504 4.2.2, respectively. After the project is created, the tool retrieves the most similar projects from  
 505 the database. Then, the tool combines the risks of these similar projects with their response  
 506 information, probabilities, and impacts. Finally, the template risk register is created and  
 507 displayed by the tool. The “risk manager” could modify the register in case of need. A risk and  
 508 response catalogue could be used during this modification. As shown in Figure 6, the second

509 workflow is monitoring the risks and updating the risk register in the light of captured risk-  
 510 related knowledge. Knowledge capture is the responsibility of both “risk supervisor” and “risk  
 511 assessor”. The actual risk impact values, the effectiveness of risk response plans, new risks that  
 512 emerged during the project are continuously monitored, calculated, and entered the system. The  
 513 CBR risk tool also displays information about project risks. In this respect, the system could be  
 514 used to get information about project risks and risk responses.

515 **Table 4.** Project features and their normalized weights (adopted from Ling et al. (2004), Han  
 516 et al. (2007), Eybpoosh et al. (2011), Fidan et al. (2011), Nguyen et al. (2015) and Eken et al.  
 517 (2020))

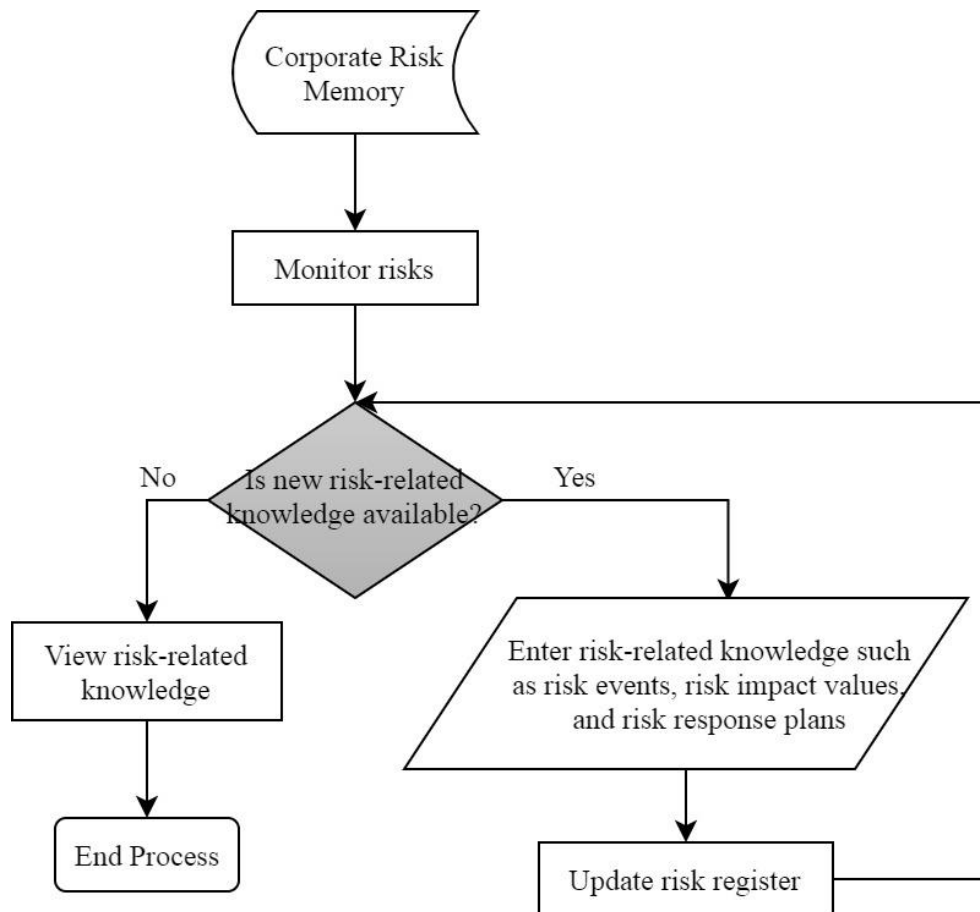
Main Features	Normalized Weights of Criteria	Sub-criteria	Formats of the features	Normalized Weights of the Sub-criteria
Project type	0.0741	-	CS	-
Country	0.0873	-	CN	-
Delivery system	0.0751	-	CS	-
Project value	0.0929	-	CN	-
Duration	0.0727	-	CN	-
Total	0.0632	-	CN	-
Contract type	0.0962	-	CS	-
Design-related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

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



518

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



519  
520

**Figure 6.** Flowchart for risk monitor process

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522 **6.2.Development of case retrieval mechanism**

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

532           **6.2.1. Determination of project features**

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

550   Although the country project feature was stated as one of the important features in the literature,  
551   studies such as Eken et al. (2020) measure the similarity between historical and target cases  
552   based on the name of the countries. In other words, if the projects are placed in the same country,  
553   the similarity between these projects is assigned as one, otherwise, the similarity is zero.  
554   However, these countries may have much more in common, and similarity between them cannot  
555   be measured based on their names. Therefore, in this study, the similarity between countries is  
556   calculated based on their risk ratings which are crisp numbers. Thus, the accuracy of the system  
557   was improved. There are different organizations providing information about the risk ratings  
558   for the countries, however, in this study, the risk rating database is prepared by using Credendo  
559   (2019). Country risk ratings change over time and/or company experience in each country may  
560   indicate a different risk rating for the country. Thus, the risk manager can modify these ratings  
561   within the tool.

562 **6.2.2. Determination of weights**

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

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

590 **Table 5.** 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.	PhD.	
	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)

591

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

### 600 **6.2.3. Hybrid similarity measurement method**

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

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

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

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

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

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

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

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

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

625 3) In the fuzzy linguistic variable format, values are linguistic variables such as high,  
 626 extremely high, high, medium, low, extremely low, definitely low. Each of these  
 627 linguistic variables is represented by a triangular fuzzy number and these numbers are  
 628 (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,  
 629 0.33) and, (0, 0, 0.17), respectively. The retrieval mechanism measures the similarity  
 630 between these triangular fuzzy numbers by using Eqns (4) to (5). In the following  
 631 equations,  $p_{ij}$  and  $p_{0j}$  are denoted as  $p_{ij} = (p_{ij}^a, p_{ij}^b, p_{ij}^c)$  and  $p_{0j} = (p_{0j}^a, p_{0j}^b, p_{0j}^c)$ .



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

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

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

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

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

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

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

### 636 6.3. Features and benefits of CBRisk Tool

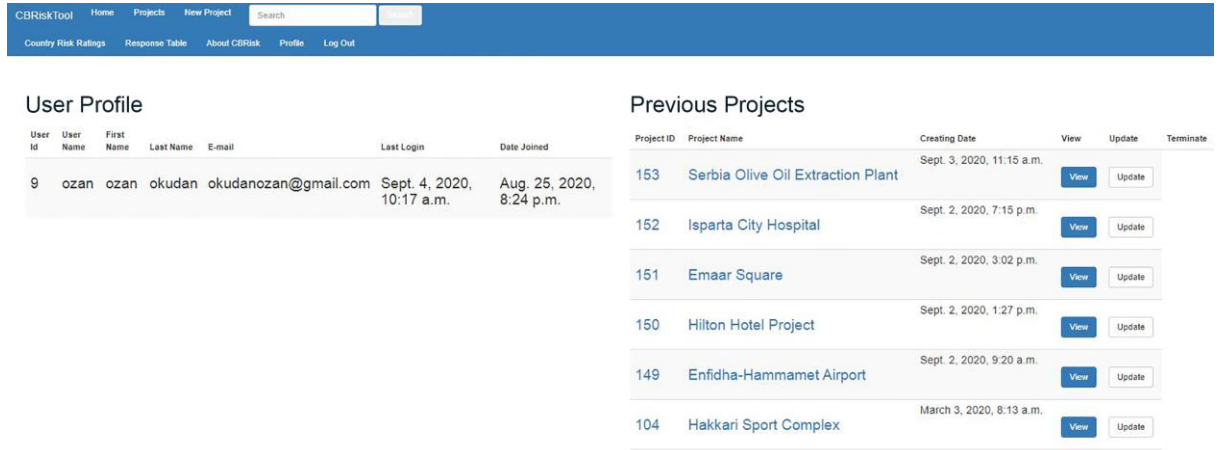
637 The latest version of the tool is available at [www.cbrisk.site](http://www.cbrisk.site). In total, the tool's user and admin  
 638 panel contain "35" screens and several of these screens were shown in Figures 7 and 8. Some  
 639 features and potential benefits of CBRisk are summarized as follows:

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

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

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

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**Figure 7.** The main screen of the tool

Risk ID	Risk Name	Risk Event	Impact	Strategy	Response	Responsible	Update
231	Inconsistencies in Design and Construction	Lack of coordination between the design and construction team	5.0	Mitigation	Coordination between the design and construction team was crucial to meet time and cost expectations. The main issue was that the construction tea...	Design Department	<a href="#">Update</a>
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	<a href="#">Update</a>
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	<a href="#">Update</a>
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 f...	Design Department	<a href="#">Update</a>
424	Unforeseen Ground Conditions	The total construction area of the project was 11 km <sup>2</sup> . 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	<a href="#">Update</a>
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	<a href="#">Update</a>
341	Incompetent Suppliers	10 new cranes were acquired from Saect which is Spanish tower crane manufacturers. 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	<a href="#">Update</a>
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	<a href="#">Update</a>

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

## 692 7. Validation of the Tool

693 Validation of the tool was carried out with a two-step procedure as shown in Figure 1. Initially,  
 694 the research team tested the functionality of the tool by using black-box testing methods. This  
 695 test was necessary to ensure that all functions integrated into the tool work properly. Within  
 696 this context, 20 hypothetical projects together with their risk-related information were entered  
 697 into the tool. These projects represent the risk memory of the construction companies. Then, a  
 698 new project was created, and all the above-mentioned RM processes were initiated for this  
 699 project as a simulation of the real case. After creating a project, the similarity measurement

700 mechanism was firstly tested whether it is capable of retrieving similar projects or not. Initially,  
701 it is realized that the mechanism worked as expected but its response time was long. Thus, a  
702 series of efforts were made to reduce this response time to an acceptable level. Upon this  
703 development, template risk register prepared by the tool based on previous projects was tested.  
704 This template risk register should have included all risks of similar projects, probability, and  
705 impact of each risk, and lists of risk responses generated for each risk. Eventually, the template  
706 risk register passed the test. Thirdly, the tool's knowledge capture feature was tested by  
707 inserting, modifying, and deleting risk-related knowledge. The knowledge capture feature was  
708 approved by the research team and the process was terminated. However, it was detected that  
709 the system failed to save the final risk register to the database due to an error with the  
710 "Terminate" button. This bug was therefore fixed, and the test was finalized. Fourthly,  
711 authorizations given to each user role were controlled so that potential operational problems  
712 arising from unauthorized interventions are avoided. Consequently, the tool's all functions were  
713 tested under similar circumstances of engineering practice and test results revealed that all  
714 functions such as similarity measurement mechanisms and risk catalogue work flawlessly.

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

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

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

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

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

- 761      iii.    All participants approved that the similarity measurement mechanism provides logical  
762            and accurate results. Besides, “Respondents 2 and 3” stated that their company has  
763            currently been attempting to establish corporate risk memory, however, their system  
764            was excel-based and lacks any similarity measurement mechanism. Considering the  
765            size of this database, they accepted that it is a challenging issue to find similar projects  
766            in the absence of a similarity measurement mechanism. On the other hand, all of the  
767            respondents found project features sufficient to represent all critical areas of the  
768            construction projects. However, “Respondent 3” argued that “the availability of special  
769            construction materials in the project” could be added as an additional project feature.  
770            He emphasized that the availability of special materials poses a great risk to projects  
771            since they necessitate additional skills, machinery, and processes.
- 772      iv.    All experts appreciated the tool’s ability to assist decision-makers on RM processes  
773            such as risk identification, risk analysis, and generating risk responses. “Respondent  
774            1” proposed that the tender specialist tremendously benefits from this tool since the  
775            tool offers a template risk register based on similar past projects. “Respondents 2 and  
776            4” stated that even inexperienced tender specialists could carry out effective RM with  
777            the guidance of this tool.
- 778      v.    The tool’s risk monitor function was found sufficient to capture risk-related knowledge  
779            from the construction projects. They all agreed that the risk catalogue consists of a  
780            wide range of risks that can be emerged throughout the project's life cycle and has the  
781            potential to ease risk identification during the risk monitor process. Especially,  
782            “Respondents 4” pointed out that capturing and storing risk-related knowledge of  
783            future projects guarantee that this tool will continue to be effective in the future.  
784            However, according to “Respondent 2”, the system might show the user’s activity logs  
785            to avoid improper entry of data. Besides, “Respondent 2” believes that tracking activity  
786            logs of the users can be used to encourage employees to make contributions to the  
787            system since it makes rewarding highly active users possible.
- 788      vi.   All respondents favoured the web-based structure of the tool. “Respondent 3” stated  
789            that they have used several web-based systems in his company and employees in the  
790            head office can easily access the system to get information even about overseas  
791            construction projects. Additionally, “Respondents 2” appreciated that the tool does not  
792            require a huge amount of technological investments. He emphasized that even

793 medium-sized companies can implement this system since it requires modest  
 794 investment. On the other hand, “Respondent 1” suggested that this tool could be further  
 795 integrated into ERP or BIM systems to increase its effectivity

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

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

803 **Table 6.** 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 catalogue presents a wide range of risks that can be emerged throughout the project’s life cycle	5	5	5	5	5
How well does the system aid decision-makers during the RM of the construction projects at the pre-project stage?	6	6	6	6	6
How well does the system achieve the concept of capturing the information related to risk?	5	5	6	5	5.25
How well is the interface of the system?	5	6	6	6	5.75

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

804 **8. Summary of Findings and Conclusions**

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

823 The functionality of the tool was initially tested by the research team. Various tests were  
824 performed by using black-box testing methods and any flaws detected during these tests were  
825 corrected immediately. During the tests, firstly, 20 hypothetical projects and their risk-related  
826 information was entered into the database. Secondly, another hypothetical project was created  
827 within the tool and all RM processes were initiated for this project. Namely, the RM of a  
828 construction project was simulated. Consequently, all functions and components passed the  
829 tests and were approved by the research team. After the functionality tests, the tool was tested  
830 by European and Turkish construction professionals. Since construction professionals are the  
831 potential users of the system, the second test was tremendously necessary to measure the



832 performance of the tool. The opinions of the experts were collected through expert review  
833 meetings. In these meetings, all details of the tool and process model were presented to experts  
834 and then, their opinion was asked. Results of the expert review meeting revealed that risk-  
835 related knowledge of previous projects is vital know-how for the construction companies and  
836 CBRisk is a useful tool to capture and use this knowledge. The CBRisk can also strengthen the  
837 competitive position of companies by safeguarding the companies against the high-employee  
838 turnover with a formal corporate risk memory. The benefits of the knowledge-based RM  
839 process model were also verified by the experts. The results indicated that continuous RM  
840 throughout the life cycle of the project may aid decision-makers to develop proactive risk  
841 response strategies that emerge during a project. Given the fact that prevention is always better  
842 than cure, proactive response strategies are certainly the key to achieve project objectives.  
843 Experts verified that a case-retrieval mechanism is a must to facilitate effective knowledge-  
844 based RM. They stated that construction companies may have a high number of projects within  
845 their portfolio. Thus, it would be challenging to find similar projects to a forthcoming project  
846 from a large database. The similarity measurement mechanism developed in this study was  
847 verified to provide reliable results. However, results indicated that minimal modifications shall  
848 be necessary before its actual implementation in practice and can be tailor-made considering  
849 specific company needs such as the size and types of projects carried out by the company. Live  
850 knowledge capture, inter-project learning and web-based architecture had initially been  
851 considered as one of the most critical strengths of the CBRisk. The results of the expert review  
852 meeting also pinpointed that these features may have significant benefits in practice.

853 It is believed that this research has theoretical contributions. Research gaps in knowledge-based  
854 RM systems were identified from the literature and CBRisk was developed to fill these gaps.  
855 CBRisk was established on a web-based platform and integrated with a case retrieval  
856 mechanism to effectively capture and reuse risk-related knowledge of previous projects.  
857 CBRisk provides a solution for a cyclic RM process supporting each step of RM from risk  
858 identification to risk monitoring. Moreover, this study contributes to the literature by integrating  
859 all steps of CBR and RM for the first time. It presents a detailed answer of how a complete  
860 CBR system can be integrated into a knowledge-based RM tool, which can be used by other  
861 researchers who aim to develop similar tools. The case retrieval mechanism developed in this  
862 study provides an advanced and accurate similarity measurement system owing to the use of

863 fuzzy logic, the use of numerous project features, and hybrid similarity measurement as  
864 proposed by Fan et al. (2014), and further be used in forthcoming studies.

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

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

894 tools in construction companies. Thus, future studies shall investigate the feasibility of  
895 deploying such a system by considering short-term costs and long-term benefits.

## 896 **9. Acknowledgment**

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