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DESIGN AND PILOT RUN OF FUZZY SYNTHETIC MODEL (FSM) FOR RISK EVALUATION IN CIVIL ENGINEERING

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Abstract. Most of the current construction risk assessment tools deliver unsatisfactory results because the prerequisite for their effective applications rely on the availability of high quality data especially during the early stage of a project. Unfortunately, such data are limited, ambiguous or even not exist due to the great uncertainty inherent in construction projects. Based on Fuzzy Synthetic Analysis (FSA), a model development team was formed among construction engineers, IT professionals, and Mathematicians in developing a holistic risk assessment model to estimate the construction risks especially for the situations with incomplete data and vague environments. Through qualitative scales defined by triangular fuzzy numbers used in pairwise comparisons to capture the vagueness in the linguistic variables, a risk assessment model using Analytic Hierarchy Process (AHP) was developed. The Pilot Run revealed the developed Fuzzy Synthetic Model (FSM) could accelerate the decision-making process and provide optimal allocation of project resources to mitigate possible risks detrimental to the success of a project in terms of time, cost, and quality.

Keywords: Fuzzy-AHP, Fuzzy Multi-criteria Decision Analysis, Triangular Fuzzy numbers, risk assessment, Fuzzy linguistic scale.

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1. Introduction

In the past few years, several quantitative-based approaches have been introduced for construction risk management such as Fault Tree Analysis, Monte Carlo Analysis, and Sensitivity Analysis (Ahmed *et al.* 2007). These sophisticated methods could deal with massive numerical data to deliver reliable statistical risk result. However, the availability of high quality data especially during the early stage of projects is a prerequisite for their effective applications (Sii, Wang 2003). Unfortunately, such data are limited, ambiguous or even not exist due to the great uncertainty inherent in construction projects. Therefore, the quantitative approaches could not suitably and effectively handle the risks (Franceschini, Galleto 2001).

In the mid of 1960s, Professor Lofti Zadeh introduced fuzzy logic to mathematically represent the uncertainty and vagueness inherited in the real world (Zadeh 1965). Scholars have presented the use of fuzzy logic in construction projects such as duration management (Zieliński 2005; Chen, Hsueh 2007), cost estimation (Cheng *et al.* 2010; Idrus *et al.* 2011), risk management (Zhang, Zou 2007; Lee, Lin 2010), safety management (Dağdeviren, Yüksel 2008), supply chain management (Chen, Huang 2006; Wei *et al.* 2007) and earned value management (Naeni *et al.* 2011). The extensive application of Fuzzy logic in the realm of construction demonstrated its easiness to be developed, understood and applied (Kasabov 1996). According to Dweiri and Kablan (2006), fuzzy logic is an excellent tool that could greatly improve the chances of achieving a better quality construction project. Eventually, it resulted in superior project performance and subsequent project success in the field of construction. Fuzzy logic is a tool to deal with decision-making environments characterized by vagueness, impression, and subjectivity (G., Bojadziev, M. Bojadziev 2007). The integration of Fuzzy logic in project risk management could give rise to satisfactory results by effectively addressing the uncertainties and subjectivities associated with construction activities. Moreover, fuzzy logic provides a more realistic way than traditional mathematical models to cope with problems that are vague in nature (Heshmaty, Kandel 1985). Based on Fuzzy Set Theory (FST), this study intends to develop a holistic risk assessment model using to estimate the construction risks especially for situations with incomplete data and vague environments. This paper introduces the principles and algorithm of its risk assessment framework. Further, a Pilot Run for the developed Fuzzy Synthetic Model (FSM) is presented.

2. Fuzzy logic and FST in construction risk management

Fuzzy Set Theory (FST), or, Fuzzy Logic, resembles human ability in inferring an approximate answer to a question based on a store of knowledge that is vague, inexact, incomplete, or not totally reliable (Zadeh 1978). In other words, Fuzzy logic simulates the way human brain works to solve real-world problems (Yager 2002) such as in forecasting, decision making, and management, which are characterized by uncertainty, impression, and subjectivity (G. Bojadziev, M. Bojadziev 2007; Negnevitsky 2004).

No construction project is risk free. Risk can be managed, minimized, shared, transferred or accepted. It cannot be ignored (Latham 1994). Over years, scholars have proposed a variety of risk management methodologies for real practise, yet most of them are similar in process, following a systematic three-step approach: identify, assess, and mitigate construction risks (Flanagan, Norman 1993; Berkeley *et al.* 1991; Lyons, Skitmore 2004). Out of the three steps, risk assessment process is the most controversial issue (Baloi, Price 2003). Meantime, there were a few research studies attempted to use FST to formalize subjectivity issues in the construction risk analysis. One of the earliest FST-based approaches was outlined by Nguyen (1985) to solve decision-making problems during the selection of bid contracts. Kangari and Riggs (1989) presented a composited fuzzy-knowledge-based system to analyze risk but revealed the limitations of probability-based approach in risk assessment process: difficult in the quantifying qualitative data, where precise data is unavailable in real situation. This issue activated the subsequent courses of exploration to investigate the fatal weakness of the probability approach in construction project risk evaluation.

Being pioneers in adopting Analytic Hierarchy Process (AHP) within construction decision problem analysis, Mustafa and Al-Bahar (1991) assessed risks through the appraising of probability and impact of risk occurrence. AHP was developed by Saaty (1980, 1990) to cope with complex decision-making problems. AHP was applied by Dey *et al.* (1994) and Riggs *et al.* (1994) to combine objective and subjective data as an attempt to analyze cost risk where risk was modelled as Probability-Impact (P–I). Zhi (1995) proposed using AHP to evaluate risk in international projects. Chun and Ahn (1992) on the other hand, integrated FST into risk analysis model to quantify the imprecision inherent in the accident progression event trees. Using FST, Paek *et al.* (1993) established a risk algorithm for the assessment of bidding price of construction projects. Wirba *et al.* (1996) applied FST to capture human reasoning in the identification and evaluation of risks.

In the 2000s, since the outset of millennium, there have been rigorous investigations to efficaciously model and evaluate the construction project risk. Risk began to be dealt comprehensively using multi-criteria decision-making (MCDM) techniques to facilitate the complex decision-making process in risk assessment. Despite the availability of many others techniques, both AHP and FST turned out as the most favoured methodologies in handling ill-defined subjective problems. They were perceived as the best ever approaches in problem-solving that encompassing multiple criteria. For instance, Hastak and Shaked (2000) proposed an AHP model to assess the risk of overseas projects. Baccarini and Archer (2001) used both the probability and impact risk parameters to rank project risks. Likewise, Jannadi and Almishari (2003) attempted to analyze risks concerned with project activities. Risk is modelled by probability and "exposure" to all hazards of an activity. Ward and Chapman (2003), however, criticized on the P–I risk model that it yielded unnecessary uncertainty by oversimplifying the estimation of risk impact and probability.

Zhang (2007) expounded the deficiencies of the P–I grid. Alternatively, "project vulnerability" is introduced to enhance the recognition of risk consequences. In the same year, Cagno *et al.* (2007) used the P–I risk model to quantify the cost risk by determining the sources of risks, affected activities, and risk owners. Besides, a three-dimensional risk model called Significance-Probability-Impact was presented where "significance" is defined as the degree to which a practitioner assesses risk intuitively. Recently, Cioffi and Khamooshi (2009) generated a probability-based model to estimate the overall risk impact on contingency budget. Based on both AHP and decision tree, Dey (2001) sought to effectively manage construction cost risk as early as on the inception stage. In addition, Dikmen *et al.* (2007a) adopted AHP to appraise uncertainties and opportunities of the overseas construction projects. The overall project risk level was computed by multiplying the relative impact and the relative likelihood of each risk. All the individual risk impacts were summed up to obtain final score. In contrast, Zayed *et al.* (2008) applied AHP to allocate weighs to risks before calculating the risk level. Some researchers attempted to integrate FST into risk assessment process. They focus mainly on the improvement of the efficiency of the conventional risk assessment tools, though rather new tools have been proposed by Huang *et al.* (2001) and Cho *et al.* (2002). Using the risk hierarchical breakdown structure, Tah and Carr (2000) proposed a fuzzy qualitative risk assessment model, where experts' subjective judgments were captured within the model to assess the risk impact. Noticing the drawback of FST in such an application, Tah and Carr (2001) proposed a new combination rule in the aggregation process of a predominant risk factor. Choi *et al.* (2004) developed a FST model to analyze risks using objective probabilities, subjective judgments, and linguistic variables. Similarly, Shang *et al.* (2005) designed a Fuzzy-based mechanism for risk assessment for the conceptual design stages of a construction project. Zheng and Ng (2005) applied FST to assess the cost and budget in construction projects.

In addition, Thomas *et al.* (2006) generated a fuzzy fault tree to enhance risk assessments by considering the opinions of different experts. A fuzzy decision-making model was designed by Wang and Elhag (2007) for a bridge construction project. The model evaluates risks based on the likelihood and consequences of occurrence. In consideration of overseas projects, Dikmen *et al.* (2007b) adopted an influence diagrams to create a fuzzy risk assessment approach to prioritize risk based on cost excess of budget. Meanwhile, Zeng *et al.* (2007) used FST to cope with uncertainty whereas AHP was applied to decompose and to prioritize multiple risk sources. Risks were first described in linguistic values and later transformed into fuzzy numbers. In the most recent, Lee and Lin (2010) suggested the use of AHP in fuzzy risk assessment in construction projects. Linguistic terms and Fuzzy numbers were directly adopted, rather than the use of quantitative data in risk assessment process. Likewise, Nieto-Morote and Ruz-Vila (2011) presented a risk assessment framework based on the FST, which could effectively capture the subjective judgements decompose large number of risks. The most notable distinction was the adoption of a risk discrimination algorithm to solve the inconsistencies in the computation process. Table 1 overviews the developed risk assessment techniques from 1980s till the year of 2011.

3. Fuzzy Analytic Hierarchy Process (Fuzzy-AHP)

Fuzzy-AHP has been extensively adopted to solve qualitative MCDM problems in the context of construction risk assessment. Together with hierarchical structure analysis, FST could excellently handle the ambiguity inherited in the conventional data evaluation process, which encompasses identification, evaluation, and prioritization of the MCDM problems (Chen 2001). One of the significant aspects of Fuzzy-AHP is its ability in solving ill-defined and vague problems in construction projects and reaching a reliable final decision (Zeng *et al.* 2007; Zhang *et al.* 2002; An *et al.* 2005). Being proven to be more advanced and efficacious in tackling complex MCDM problems, Fuzzy-AHP generally follows a process, structured in a three-step approach, namely: a) generation of risk hierarchy tree; b) pairwise comparison to establish fuzzy comparison matrix; c) fuzzy prioritization of criteria.

3.1. Generation of risk hierarchy tree

Taxonomy of a typical hierarchy tree associated with construction project risks is shown in Figure 1. The complex decision problems can be formulated in the form of simple hierarchy tree. The overall goal is placed at the highest level. The criteria affecting the goal are located in the middle levels. The lowest level presents the decision options. Before the hierarchy tree is structured, different risk factors have to be exhaustively recognized. Usually, the construction practitioners have intuitive methods of recognizing a risk source. This is in accordance with the statement of Wang *et al.* (2004) that experts prefer to intuitively identify risks using experience and knowledge gained from previous contracts. There are, anyhow, some formal risk identification tools such as Checklist, Influence Diagrams, Cause and Effect Diagram, Failure Mode and Effect Analysis, and Fault Trees Analysis (Zavadskas *et al.* 2010; Tah, Carr 2000).

Nevertheless, large construction projects tend to adopt formalized risk identification tools, and vice versa. All the sources of uncertainties identified are classified within the hierarchy tree structure so that they can be thoroughly evaluated. Various risk classification methods are shown in Table 2. The methods adopted to classify construction risks depend largely on the nature of a project as well as the management skills of experts. Once the decomposition of risk problems into a hierarchy tree is completed, risk assessment process is carried out to determine the relative importance, dominance or preference of the decision criteria with regards to the goal of the problems.

3.2. Pairwise comparison to establish Fuzzy comparison matrix

The importance weighs of criteria is determined in the pairwise comparison manner. Anyhow, the difference between pairwise comparison process in Fuzzy-AHP and normal AHP is in the use of Fuzzy comparison scale, where Fuzzy numbers are integrated into the original comparison scale to substitute the nine exact numbers in Fuzzy-AHP. Experts could intuitively express their preferences as the Fuzzy numbers could accurately describe the expert's verbal judgments in the process Zadeh (1965). The Fuzzy comparison scale works excellent in capturing the subjective experience and knowledge of experts through the application of the Fuzzy numbers (Chang, Yeh 2002; Kahraman *et al.* 2004) within Fuzzy-AHP. Using the advanced comparison scale, experts could express their judgments using natural languages such as "equally important" and "absolutely more important" which

Table 1. Overview of risk assessment approaches from 1980s to 2000s

Period of Time	Author	Risk Assessment Approach/Methodology	Assess Risk against Project Objective: Yes	No
1980s	Chapman and Cooper (1983)	PERT, decision trees & probability distributions	Time	
	Cooper *et al.* (1985)	Risk breakdown structure & variation distribution	Cost	
	Nguyen (1985)	FST	Cost	
	Franke (1987)	Probability theory	Cost	
	Kangari and Riggs (1989)	FST		√
The 1990s	Yeo (1990)	Probability, Range estimates method & PERT	Cost	
	Mustafa and Al-Bahar (1991)	AHP		√
	Diekmann (1992)	Probability		√
	Chun and Ahn (1992)	FST & event trees		√
	Paek *et al.* (1993)	FST	Cost	
	Dey *et al.* (1994)	AHP	Cost	
	Riggs *et al.* (1994)	AHP	Cost & time	
	Zhi (1995)	AHP		√
	Williams (1995)	Probability	Quality	
	Wirba *et al.* (1996)	FST		√
	Tavares *et al.* (1998)	Stochastic model	Cost & time	
	Mulholland and Christian (1999)	Probability & PERT	Time	
The 2000s	Hastak and Shaked (2000)	AHP and Probability		√
	Tah and Carr (2000)	FST		√
	Dey (2001)	AHP & decision trees	Cost	
	Tah and Carr (2001)	FST		√
	Baccarini and Archer (2001)	Probability	Cost, time & quality	
	Cho et *al.* (2002)	FST		√
	Ward and Chapman (2003)	6-steps minimalist approach		√
	Baloi and Price (2003)	FST	Cost	
	Jannadi and Almishari (2003)	Probability	Time	
	Choi *et al.* (2004)	FST		√
	Shang *et al.* (2005)	FST		√
	Dikmen *et al.* (2007a)	AHP		√
	Cagno *et al.* (2007)	Probability	Time	
	Zhang (2007)	Probability		√
	Wang and Elhag (2007)	FST		√
	Zeng *et al.* (2007)	FST & AHP		√
	Zheng and Ng (2005)	FST	Cost & time	
	Zhang and Zou (2007)	FST & AHP		√
	Dikmen *et al.* (2007b)	FST & AHP	Cost	
	Han *et al.* (2008)	Probability	Cost	
	Zayed *et al.* (2008)	AHP		√
	Cioffi and Khamooshi (2009)	Probability theory	Cost	
	Lee and Lin (2010)	FST		√
	Nieto-Morote and Ruz-Vila (2011)	FST & AHP		√

are directly corresponding to Fuzzy scale of (1, 1, 1) and (17/2, 9, 19/2), respectively. Reciprocal scale is adopted whenever the later criterion j is more dominant than the former criterion i. As such, the expert no longer face difficulty in giving fixed judgments, which is in the form of exact numbers, but rather interval judgments, which is in the form of Fuzzy numbers. There are various types of Fuzzy numbers proposed in Fuzzy comparison scale, yet the triangular and trapezoidal shapes are the most frequently used membership functions in construction risk analysis practice due to their simplicity in application (An *et al.* 2005). They have been proven to be able to efficaciously formulate problems where the data available is of subjective and vague (Kahraman *et al.* 2004; Chang *et al.* 2007). In comparison, the triangular shape membership functions are the most often used in representing the Fuzzy numbers (Karsak, Tolga 2001)

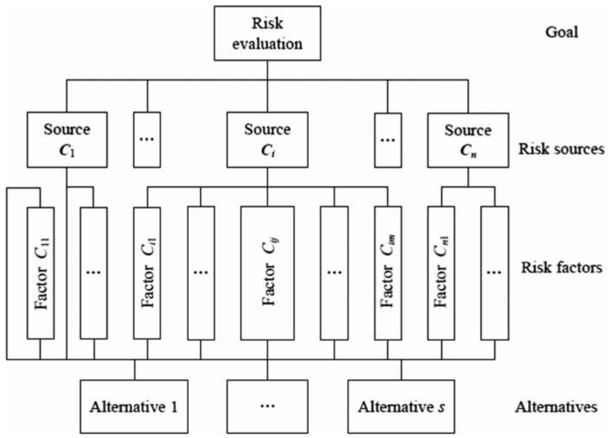

Fig. 1. Theoretical model of risk evaluation (Sun *et al.* 2008)

in the Fuzzy comparison scales. Likewise, Pedrycz (1994) expressed that a triangular Fuzzy number (TFN) is the easiest and simplest way to approach the convex functions. Moreover, if the pairwise comparison process involves group-decision-making, the experts' preferences on particular criterion have to be aggregated. This is because experts with different background and experience would have different preference on a particular criterion. Hence, it needs to aggregate the individual preferences into the group preference to average out the relative importance weightings of the criteria. The aggregation process is carried out for every criterion, until all criterions have their own group preferences. The groups preferences, which are remain in Fuzzy numbers, are arranged in a systematic manner to yield a Fuzzy comparison matrix. Pairwise comparison is used to calculate the relative importance weighing of each risk criterion with the incorporation of Fuzzy numbers to capture the subjective expert's judgments in the process. The output is a Fuzzy comparison matrix (Ding, Liang 2005; Xu, Chen 2007).

Table 2. Previous introduced risk classification methods

No.	Author	Risk Classification method	Grouping risk based on:
1	Cooper and Chapman (1987)	Nature and magnitude	Primary and secondary risk
2	Wirba *et al.* (1996)	Risk-breakdown structure	Minor and major risks
3	Tah and Carr (2000)	Risk-breakdown structure	External and Internal factor
4	Dikmen *et al.* (2007a)	Influence Diagram	Project risk & Country risk
5	Zayed *et al.* (2008)	Hierarchy structure	Macro and micro level
6	Nieto-Morote and Ruz-Vila (2011)	Hierarchy structure	Responsibility of the Construction practitioners

3.3. Fuzzy prioritization of criteria

Since Saaty (1980) had proposed the AHP, many researchers enrolled in the extension of the eigenvector priority method to overcome its inconsistency in producing results. As an attempt to produce reliable final priority weighs, researchers adopted different types of Fuzzy prioritization approaches, for instance, the earliest attempt in prioritizing fuzzy weighs was accomplished by van Laarhoven and Pedrycz (1983) in which triangular fuzzy numbers were compared according to their membership functions. Likewise, Buckley (1985) used trapezoidal fuzzy numbers to integrate the fuzzy priorities of comparison ratios. A new approach called Fuzzy Synthetic Analysis (FSA) for computation of a sequence of weigh vectors (Chang 1996) suggested the application of extent analysis method for the synthetic extent values of the Fuzzy pairwise comparisons. The term "synthetic" expresses the process of evaluation whereby several individual criterions of an evaluation are synthesized and aggregated to a final form. Despite the diversity of Fuzzy prioritization approaches, FSA is the most abundant used method in the literatures indicating its popularity in prioritizing decision variables. It has been perceived as the best prioritizing method due to its simple and easy in application (Chan, Kumar 2007).

4. Methods and procedures in developing FSM

To appropriately conduct the qualitative technique in the development of FSM, a developing team was established consisting of construction engineers, IT professionals, risk managers, and mathematicians. Owing to the nature of the developers where their experiences, perceptions, and opinions are necessities to the enhancement of the model, the qualitative approach was adopted in this study. The qualitative technique enables on-the-spot directness to the information in which rapid, immediate response could be obtained from the elites, where it is not possible when the quantitative technique such as questionnaire surveys are conducted. The developing team consists of a range of experts of different specialties, whose detailed information regarding their contribution towards the birth of FSM is summarised in Table 3.

The use of probability theory to deal with the construction project of one-time characteristic complicates the risk analysis process. Conventional approaches are impractical in those real situations where high quality data are absent yet they could not effectively deal with the subjective human assessments, for instance, the fixed scale of 1–9 used in the pairwise comparison process is incapable to

Table 3. Developers' profiles and roles in the development of FSM

Developer	Age	Gender	Location	Specialty/Area	Roles in Developing the FSM	
A	52	Male	Kuala Lumpur	Project Monitoring	**Preliminary step:** Selection of Risk Analysis Approach	Considering the limitation of conventional AHP models in yielding reliable results owing to their inability to effectively quantify subjective data, Developer A aroused the idea of integrating fuzzy tools into the AHP to further enhance the efficiency and practicability of the model. Accordingly, the team decided to synthesized FST, which was proven as an excellent tool to capture uncertain and subjective qualitative data in decision-making process, within the developed model.
B	37	Male	Kuala Lumpur	Fuzzy Model Development	**Preliminary step:** Appearance of Model	Developer B adopted FST in the developed model although the concept was unfamiliar in the context of construction industry. Moreover, Developer B mapped how to present the model holistically. Important elements such as mathematical formulae have been added into the model to enable an explicit picture of the whole structure. The model so that could be presented in a simple but comprehensive way.
C	33	Male	Selangor	Construction Risk	**Preliminary step:** Selection of Risk Analysis Approach	Developer C captured and incorporated the subjective data of construction processes into the risk analysis techniques to increase the consistency for risk management. The real construction rarely adopt formal risk analysis tools. The only technique applied in the medium and small firms is informal technique such as rule of thumb.
D	36	Female	Kuala Lumpur	Construction IT Application	**Step 2 & 6:** Selection of Risk Parameters	Developer D provided the risk parameters used during the evaluation of risks. Both the risk likelihood and risk severity have been considered in evaluating the risk impact to avoid misleading solutions. For example, a risk with high likelihood of occurrence is not necessarily with high level of severity when it occurred.
E	49	Male	Selangor	Construction Monitoring	**Step 1:** Range of Expertise	Developer E produced risk hierarchy trees in different perspectives. Besides, Developer E identified the differences in risk management skills according to the positions of construction practitioners.
F	45	Male	Selangor	Mathematician	**Step 2:** Risk Identification	Developer F multiplied the risk parameters in the analysis to calculate the final risk impact of a particular risk.
G	31	Female	Kuala Lumpur	Risk Management	**Step 2:** Risk Identification	Developer G identified the risks based on the type and nature of projects. Besides, Developer G figured out the risk identification methods used in the model development.

Table 3 (*Continued*)

Developer	Age	Gender	Location	Specialty/Area	Roles in Developing the FSM	
H	46	Male	Kuala Lumpur	Construction Risk Modelling	**Step 2:** Project Objectives	Developer H measured risk impacts with regards to project objectives such as time, cost, and quality during the risk analysis process.
					Step 3: AHP's Comparison Method	Developer H applied Pairwise Comparison process within the developed model, where the risks were compared to determine which one was more dominance than the others in a project.
I	51	Female	Kuala Lumpur	Mathematician	**Step 4 & 5:** Mathematical Formulae	Developer I embedded the mathematical formulas into the developed FSM.

describe the interval judgment of experts. The authors adopted the Fuzzy-AHP technique as the decision-making framework for construction risk analysis in the developed model since the Fuzzy-AHP allows a more accurate description of the subjective data, where the fuzzy pairwise comparisons are more rational in reflecting experts' uncertain judgments than crisp one. Such a model could facilitate the decision-making process, where the complex uncertainty inherited in subjectivity is able to be captured and mitigated optimally. The project performance is significantly affected by construction risks in concerns of cost, time, and quality. The developed FSM is to holistically solve multi-criteria complex problems in the real practice of construction. The algorithm of the proposed model consists of six phases, which are discussed as follows.

4.1. Establishment of risk assessment team

Owing to the large burdens during the project risk analysis, the decision-making process was conducted by a group of risk assessment experts. Due to their different background, experience, and knowledge, each expert in the risk assessment team has different impacts on the final decision. The experts with higher degree of knowledge and more related experience on the targeted project have more substantial impact in the risk assessment process so that their contribution factors are given more weigh in the model. This is due to the reason that the final result is more consistent as the risk analysis process is undertaken comprehensively by different experts with various competencies. The contributions factors are used to determine the weighing for different evaluators. Basically, the relative weighing of the experts is determined by their competence on the basis of their experience, knowledge, and expertise related to the targeted project. The formulas for contribution factors are presented in Section 5. The risk assessment team is responsible to classify and to structure all potential risks within a hierarchy tree in the next step.

4.2. Structure a hierarchy tree

Structuring of a hierarchy tree aims to decompose the goal into adequate details in which all the criteria could be thoroughly assessed. Generally, the top level of the hierarchy tree is the overall goal of the decision problem. In the context of construction risk analysis, the goal is defined as risk evaluation. The subsequent levels present the general risk sources, then their specific risk factors, which are evaluated. The lowest level is the alternative of decision options, with regards to the goal, which are determined based on the kind of results desired in the end of analysis. To determine the decision criteria, it entails the understanding of the underlying factors impacting the goal. Hence it is essential to investigate all potential sources of uncertainty likely to affect a project. The recognized risks are classified in a way that the risks with similar characteristics are grouped together in the hierarchy. The construction uncertainty is commonly modelled based on the integration of two risk parameters: a) the probability of occurrence and b) severity of risk impact. The hierarchy tree was constructed as shown in Figure 2. The complex decision problems were structured within a simple hierarchical structure, where the decision criteria were placed comprehensively into five levels. The top level is defined as "Construction Project Risks" to reflect the overall goal. It is followed by two risk parameters that serve as the evaluation basis for risks. The third level is where all major risk sources are located, with their respective risk factors in the subsequent level. The lowest level presents the project objectives including time, cost, and quality.

As illustrated in Figure 2, the general risks and their specific sub-factors are located respectively in the third and the fourth level. Eventually, the project objectives such as time, cost, and quality are placed in the bottom level. It could mitigate the uncertainty depending on the relative risk impact towards the project objective. Compromises such as targeted budget, good scheduled time, and high project quality

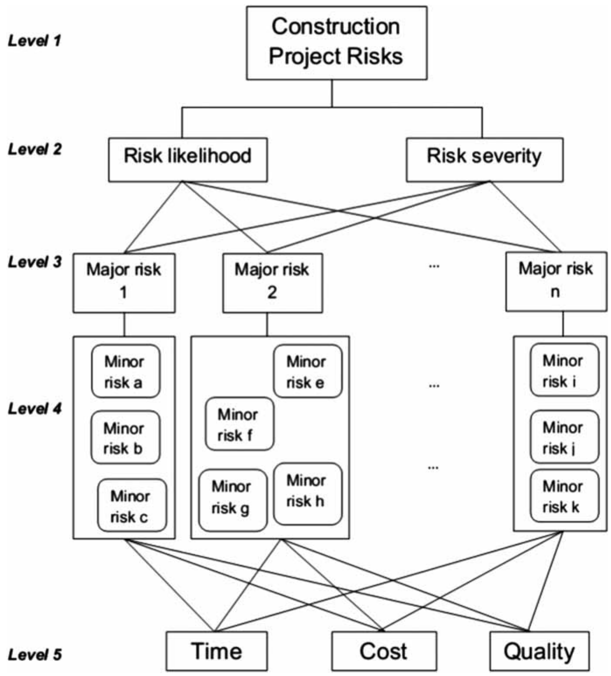

Fig. 2. Risk likelihood and risk severity

are guaranteed when all the project objectives are accomplished.

4.3. Pairwise comparison using Fuzzy comparison scale

The risk assessment process is carried out once the hierarchy tree is established. Most frequently there are multiple contradicting risk sources existing in a project. This complicates the decision-making process as the experts need to consider various criteria simultaneously. Hence, it is a necessity to prioritize risks for further attention. To do so, the experts need to firstly determine the relative weigh of each criterion in the same hierarchy, via pairwise comparison process, so that their relative priority weighs could be calculated. The greatest advantage of pairwise comparison is that the experts are allowed to focus on the comparison of just two objects, which makes the observation as free as possible from extraneous influences. To systematically capture the valuable subjective judgments of experts in the risk analysis, Fuzzy comparison scale is proven to be accurate and intuitive in reflecting the qualitative judgments where decision makers could specify preferences in the form of natural language regarding the importance of each criterion. The most common used Fuzzy numbers are both the triangular and trapezoidal Fuzzy number (TFN). In this study, the simplest form of TFN was applied for representing the linguistic judgments, as TFN was sufficient to produce a reliable result. The fuzzy scale of TFN is intuitively easy to use and to calculate so that it was adopted to improve the pairwise comparison process.

4.4. Aggregation of individual TFNs into group TFN

Every individual in the risk assessment team has a TFN preference for criterion in the hierarchy tree. The individual TFNs of particular criterion should be aggregated into the group TFN preference. The rationale of this step is to integrate all the individual TFN preferences for particular criterion so that the Fuzzy comparison matrices remain consistent. The aggregation process is completed once the individual TFNs of every criterion in the hierarchy tree are converted into group TFN. All group TFNs are arranged in a matrix structure, which is called "Fuzzy comparison matrices". Consequently, the relative priority weigh of each criterion was calculated using the Fuzzy prioritization method in the next step.

4.5. Calculation of priority weighs at different hierarchy level

It is usually not possible to address all risks with a same degree of attention, as resources available for risk management are limited. Concentration on risks with higher priority is essential for efficient risk management. This step aims to calculate the relative priority weighs of decision criteria in the same level, with respect to their upper criterions. Since the conventional eigenvector prioritization method is being doubt of its consistency, the Fuzzy prioritization method was used in this step to calculate the final priority weighs in the proposed model.

4.6. Systemization of results

The relative priority weigh of each criterion attained through previous steps was synthesized to obtain the final priority weigh. This process was computed by synthesizing all relative priority weighs of particular decision criteria from the bottom level to the top level. The outcome is a normalized vector of the overall weighs of the alternatives, which are then ranked in order. In response to the final ranking of each criterion, the users can take risk mitigation actions. Risk mitigation is a plan that reduces risk impact on the project performance. Options available for mitigation include "control", "avoidance", and "transfer". A mitigation plan could be carried out to reduce or to eliminate the risks with the selected higher priority weighs, with respect to the time, cost and quality of a project.

5. Mechanism and appearance of the developed FSM

Eventually, a Fuzzy Synthetic Model, abbreviated as FSM, was developed as shown in Figure 3. There are six steps within the model, which are delineated in the following sections.

Step 1: Establishment of Risk Assessment Team. In this step, the weighs were calculated to allocate difference contribution factors to the experts. If there

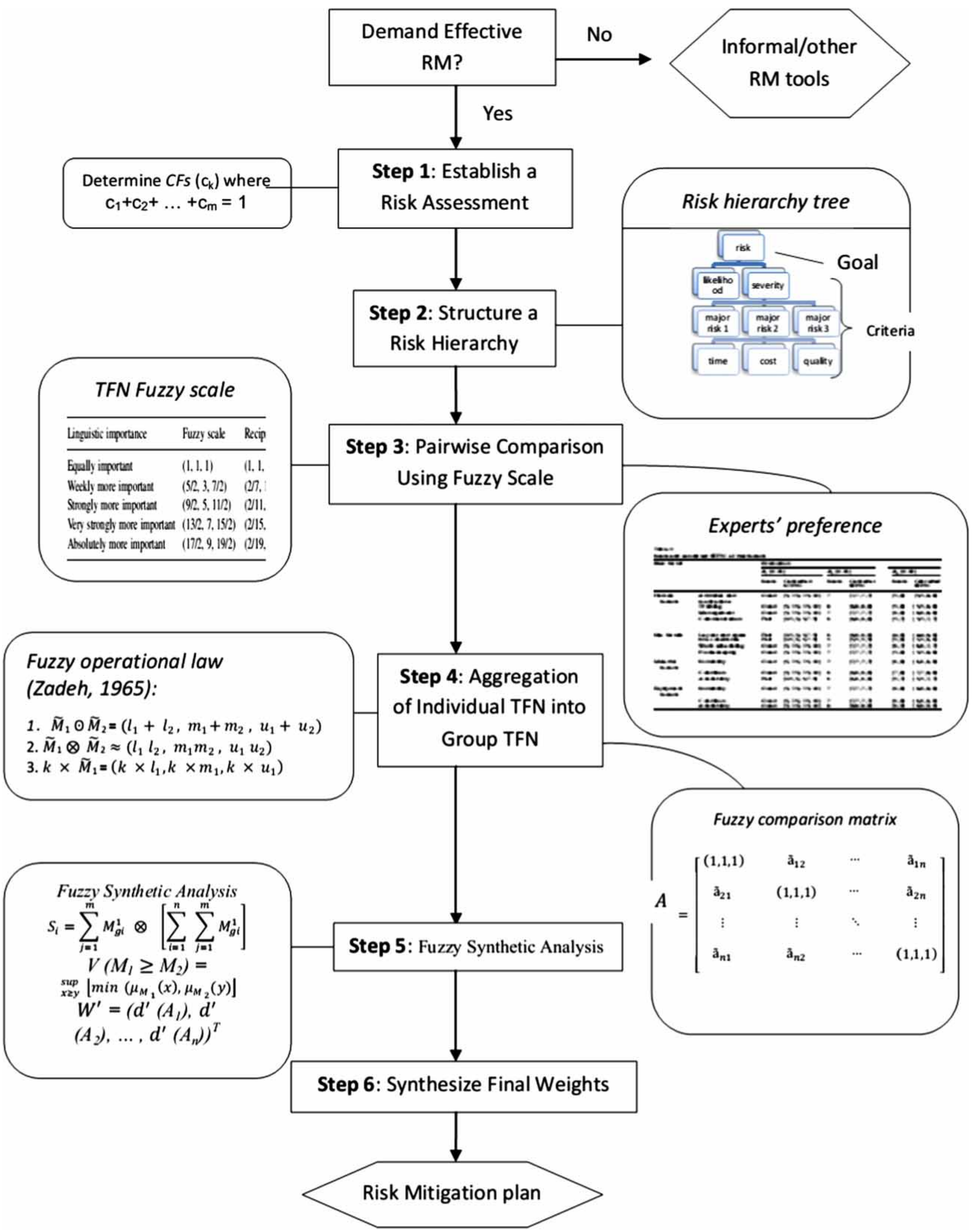

Fig. 3. The developed Fuzzy Synthetic Model (FSM)

are m experts in the risk assessment team, the k^{th} expert E_k is allocated a contribution factor c_k as defined in Eq. (1):

$$c_1 + c_2 + ... + c_m, \quad \text{where } c_k\,[0, 1]. \tag{1}$$

Step 2: Structuring Risk Hierarchy Tree. The risk identification process was conducted based on the nature of a project. This is to anticipate potential risks on the stage of project development. The intuitive method was applied. The risks identified were structured into a simple hierarchy tree. The risks are grouped on the basis of their characteristics and the level of decomposition is non-limited. It depends on the variables to be measured in a project.

Step 3: Pairwise Comparison Using Fuzzy Comparison Scale. Pairwise comparison was carried out to determine the relative importance weighs of criteria. Every expert in the risk assessment team is required to compare those risks in a pairwise manner, via fuzzy scale, to produce a Fuzzy comparison matrix as shown in Eq. (2). TFN is used to convert the corresponding linguistic judgment according to the Fuzzy comparison scale:

$$\tilde{A} = \begin{bmatrix} (1,1,1) & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\ \tilde{a}_{21} & (1,1,1) & \cdots & \tilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \cdots & (1,1,1) \end{bmatrix}, \quad (2)$$

where $\tilde{A}$ represents a fuzzified reciprocal *n-n* judgment matrix containing all pairwise comparison $\tilde{a}_{ij}$ between elements *i* and *j* for all $i, j = \{1, 2, \ldots, n\}$; û and all $\tilde{a}_{ij}$ are triangular fuzzy numbers $\tilde{a}_{ij} = (l_{ij}, m_{ij}, u_{ij})$ with l_{ij} the lower and u_{ij} the upper limit and m_{ij} is the point where the membership function $\mu(x) = 1$.

Step 4: Aggregation of Individual TFNs into Group TFN. The pairwise judgments of individual TFNs were aggregated into a group Fuzzy number using the operational laws base on Zadeh (1965), which are defined as:

– Fuzzy addition:

$$\tilde{M}_1 \oplus \tilde{M}_2 = (l_1 + l_2, m_1 + m_1, u_1 + u_2); \quad (3)$$

– Fuzzy multiplication:

$$\tilde{M}_1 \odot \tilde{M}_2 \approx (l_1 + l_2, m_1 + m_1, u_1 + u_2); \quad (4)$$

– The inverse of triangular fuzzy number $\tilde{M}$=l_1,m_1,u_1):

$$M_1^{-1} \approx \left(\frac{1}{u_1}, \frac{1}{m_1}, \frac{1}{l_1}\right); \quad (5)$$

Table 4. Experts and their respective contribution factors in the model Pilot Run

Expert (E_k)	Title	Working experience (Year)	Contribution Factor (C_k)
E_1	Project manager	7	0.22
E_2	Project coordinator	11	0.34
E_3	Contractor manager	5	0.16
E_4	Engineer in Chief	9	0.28
Total		**32**	**1.00**

– The scalar multiplication of a triangular fuzzy number:

$$k \times \tilde{M}_1 = (k \times l_1, k \times m_{10}, k \times u_1) \text{ if } k > 0; \quad (6)$$

$$k \times \tilde{M}_1 = (k \times u_1, k \times m_{10}, k \times l_1) \text{ if } k > 0. \quad (7)$$

Step 5: Fuzzy Synthetic Analysis. Fuzzy synthetic analysis was carried out to calculate the relative priority weighs of criteria. According to Chang (1996), there are three procedures involved as described below:

Procedure 1: Calculate the Fuzzy Synthetic Extent Values:

$$S_i = \sum\nolimits_{j=i}^{m} M_{gi}^1 \otimes \left[\sum\nolimits_{j=i}^{m} M_{gi}^1\right]; \quad (8)$$

Procedure 2: Calculate the Degree of Possibility:

$$V(M_1 \geq M_2) = \sup_{x \geq y} \left[min\left(\mu_{M_1}(x), \mu_{M_2}(y)\right)\right], \quad (9)$$

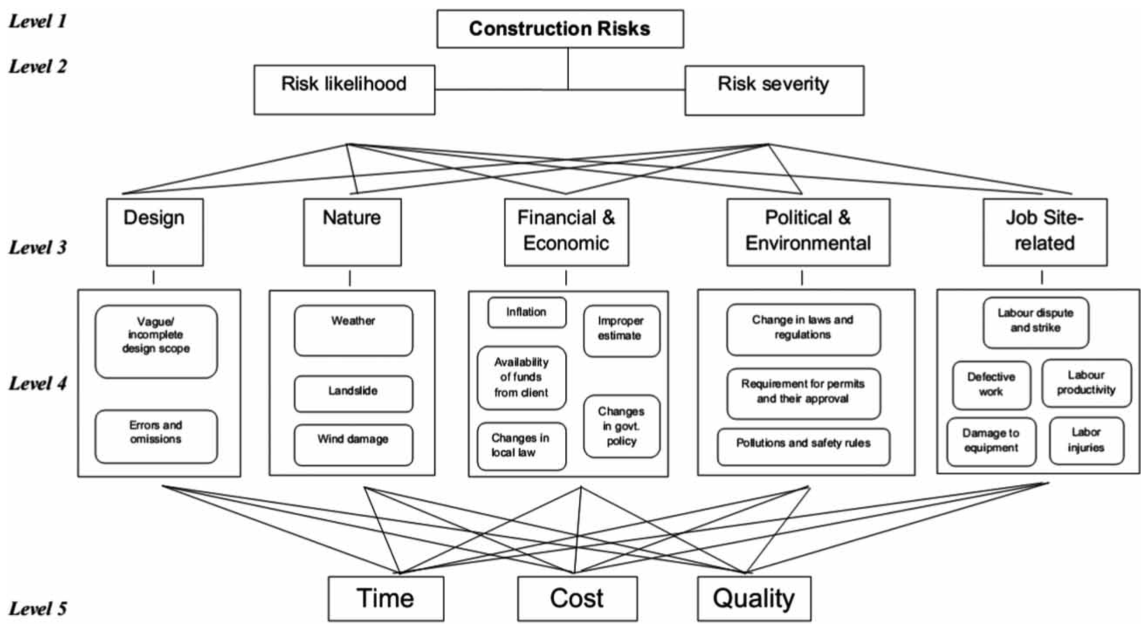

Fig. 4. Breakdown structure of construction project risks

Table 5. Evaluation of sub-criteria with respect to "Weather" (Level 4)

			Time		Cost		Quality	
			Scale	Converted TFN	Scale	Converted TFN	Scale	Converted TFN
Time	E_1	0.22			(2/7, 1/3, 2/5)		(2/11, 1/5, 2/9)	
	E_2	0.34			(2/11, 1/5, 2/9)		(2/7, 1/3, 2/5)	
	E_3	0.16			(2/7, 1/3, 2/5)		(2/11, 1/5, 2/9)	
	E_4	0.28			(2/7, 1/3, 2/5)		(2/11, 1/5, 2/9)	
	Aggregation			(1.00, 1.00, 1.00)		(0.25,0.29,0.34)		(0.22,0.25,0.28)
Cost	E_1	0.22	(5/2, 3, 7/2)				(2/7, 1/3, 2/5)	
	E_2	0.34	(9/2, 5, 11/2)				(2/7, 1/3, 2/5)	
	E_3	0.16	(5/2, 3, 7/2)				(2/7, 1/3, 2/5)	
	E_4	0.28	(5/2, 3, 7/2)				(2/11, 1/5, 2/9)	
	Aggregation			(3.18, 3.68, 4.18)		(1.00, 1.00, 1.00)		(0.26,0.30,0.35)
Quality	E_1	0.22	(9/2, 5, 11/2)		(5/2, 3, 7/2)			
	E_2	0.34	(5/2, 3, 7/2)		(5/2, 3, 7/2)			
	E_3	0.16	(9/2, 5, 11/2)		(5/2, 3, 7/2)			
	E_4	0.28	(9/2, 5, 11/2)		(9/2, 5, 11/2)			
	Aggregation			(3.82,4.32,4.82)		(3.06,3.56,4.06)		(1.00, 1.00, 1.00)

where: $V(M_1 \geq M_2) = 1$ if $m_1 \geq m_2$

$$V(M_1 \geq M_2) = hgt(M_1 \cap M_2) = \mu_{M_1}(d); \qquad (10)$$

$$V(M_1 \geq M_2) = hgt(M_1 \cap M_2) \frac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)}; \qquad (11)$$

Procedure 3: Calculate the Normalized Weigh Vectors:

$$V(M \geq M_1, M_2, \ldots, M_k) = V[(M \geq M_1) \text{ and } (M \geq M_2) \text{ and } (M \geq M_k)] = \min V(M \geq M_i),\ i = 1, 2, 3, \ldots, k. \qquad (12)$$

Assuming that:

$$d'(A_i) = \min V(S_i \geq S_k) \qquad (13)$$

for $k = 1, 2, \ldots, n$; $k \neq i$. Then the weigh vector is given by Eq. (14):

$$W' = (d'(A_1), d'(A_2), \ldots, d'(A_n))^T, \qquad (14)$$

where: $A_1 (i = 1, 2, \ldots, n)$ are n elements.

Via normalization of W′, the normalized weigh vectors are as Eq. (15):

$$W = (d(A_1), d(A_2), \ldots, d(A_n))^T, \qquad (15)$$

where W is a non-fuzzy number.

Table 6. Fuzzy comparison matrix with respect to "Weather" (Level 4)

	Time	Cost	Quality
Time	(1.00, 1.00, 1.00)	(0.25,0.29,0.34)	(0.22,0.25,0.28)
Cost	(3.18, 3.68, 4.18)	(1.00, 1.00, 1.00)	(0.26,0.30,0.35)
Quality	(3.82,4.32,4.82)	(3.06,3.56,4.06)	(1.00, 1.00, 1.00)

Step 6: Synthesizing Final Weighs. Finally, the relative priority weighs of the criteria were synthesized across the hierarchy tree to produce final weighs with respect to project objectives. Consequently, risk controlling process could take place to mitigate and monitor the highest risky uncertainty.

6. Pilot Run and validation of FSM

The Pilot Run project for the developed FSM was conducted with a G7 contractor who managed to assess the potential risks in a ten-floor high-rise building project at Kepong, Kuala Lumpur. The goal is to take into account all the possible impact of risks towards the project objectives. The Pilot Run project is presented here to validate the implementation of the developed FSM.

6.1. Pilot Run: established risk assessment team

Four experts in the G7 contractor were selected to form a risk assessment team. The profiles of these 4 experts are presented in Table 4. Prior to the risk analysis process, the contribution factor for the first expert c_1 was calculated based on his working experience related to the risk assessment on this type of construction, so that his weighing was determined by Eq. (16). Similarly, the contribution factors for other experts were calculated as shown in Table 4:

$$C_1 \, for \, E_1 = \frac{7}{7 + 11 + 5 + 9} = 0.22. \qquad (16)$$

6.2. Pilot Run: structured hierarchy tree

The hierarchy tree was structured as shown in Figure 4. The top level is the overall goal of the risk assessment problem defined as "Construction Risks"

Table 7. (Level 4) Matrices of pairwise comparisons and respective normalized weigh vectors

Vague/incomplete Design Scope: WVDS = (0.34, 0.66, 0)T				Errors and Omissions: WEO =(0.20, 0.62, 0.18)T			
	Time	Cost	Quality		Time	Cost	Quality
Time	(1.00, 1.00, 1.00)	(0.25,0.29,0.34)	(0.22,0.25,0.28)	Time	(1.00, 1.00, 1.00)	(0.07,0.12,0.18)	(0.09,0.15,0.18)
Cost	(3.18, 3.68, 4.18)	(1.00, 1.00, 1.00)	(0.26,0.30,0.35)	Cost	(4.06,4.56,5.06)	(1.00, 1.00, 1.00)	(0.12,0.17,0.21)
Quality	(3.82,4.32,4.82)	(3.06,3.56,4.06)	(1.00, 1.00, 1.00)	Quality	(5.82,6.32,6.82)	(4.13, 4.56,5.06)	(1.00, 1.00, 1.00)
Landslide: WL =(0.13, 0.48, 0.39)T				Wind Damage: WWD =(0, 1, 0)T			
	Time	Cost	Quality		Time	Cost	Quality
Time	(1.00, 1.00, 1.00)	(0.25,0.29,0.34)	(0.22,0.25,0.28)	Time	(1.00, 1.00, 1.00)	(0.31,0.39,0.44)	(0.32,0.39,0.48)
Cost	(3.18, 3.68, 4.18)	(1.00, 1.00, 1.00)	(0.26,0.30,0.35)	Cost	(3.94, 4.11, 4.68)	(1.00, 1.00, 1.00)	(0.30, 0.33,0.36)
Quality	(3.20,3.45,4.12)	(3.06,3.28,4.18)	(1.00, 1.00, 1.00)	Quality	(3.82,4.32,4.82)	(4.09,4.56,5.06)	(1.00, 1.00, 1.00)
Inflation: WI =(0, 0.40, 0.60)T				Availability of Funds from Client: WAFC =(0.05, 0.58, 0.37)T			
	Time	Cost	Quality		Time	Cost	Quality
Time	(1.00, 1.00, 1.00)	(0.25,0.31,0.34)	(0.36,0.41,0.43)	Time	(1.00, 1.00, 1.00)	(0.26,0.30,0.35)	(0.09,0.15,0.18)
Cost	(3.18, 3.68, 4.18)	(1.00, 1.00, 1.00)	(0.28, 0.30,0.38)	Cost	(4.06,4.56,5.06)	(1.00, 1.00, 1.00)	(0.20,0.25,0.30)
Quality	(3.82,4.32,4.82)	(3.06,3.56,4.06)	(1.00, 1.00, 1.00)	Quality	(5.82,6.32,6.82)	(4.13, 4.56,5.06)	(1.00, 1.00, 1.00)
Changes in Local Law: WCLL =(0, 1, 0)T				Changes in Government Policy: WCGP =(1, 0, 0)T			
	Time	Cost	Quality		Time	Cost	Quality
Time	(1.00, 1.00, 1.00)	(0.27,0.31,0.34)	(0.19,0.21,0.25)	Time	(1.00, 1.00, 1.00)	(0.06,0.10,0.17)	(0.06,0.15,0.18)
Cost	(3.20,3.45,4.12)	(1.00, 1.00, 1.00)	(0.17,0.18, 0.24)	Cost	(5.82,6.32,6.82)	(1.00, 1.00, 1.00)	(0.11,0.16,0.20)
Quality	(3.51,4.32,4.94)	(3.06,3.56,4.06)	(1.00, 1.00, 1.00)	Quality	(6.45,7.16,7.83)	(5.15,5.36,6.24)	(1.00, 1.00, 1.00)
Improper Estimate: WIE =(0.03, 0.81, 0.06)T				Changes in Laws and Regulations: WCLR =(0.46, 0.54, 0)T			
	Time	Cost	Quality		Time	Cost	Quality
Time	(1.00, 1.00, 1.00)	(0.26,0.30,0.35)	(0.09,0.15,0.18)	Time	(1.00, 1.00, 1.00)	(0.31,0.39,0.44)	(0.32,0.39,0.48)
Cost	(4.06,4.56,5.06)	(1.00, 1.00, 1.00)	(0.20,0.25,0.30)	Cost	(3.18, 3.68, 4.18)	(1.00, 1.00, 1.00)	(0.28, 0.30,0.38)
Quality	(5.82,6.32,6.82)	(4.13, 4.56,5.06)	(1.00, 1.00, 1.00)	Quality	(3.51,4.32,4.94)	(3.20,3.45,4.12)	(1.00, 1.00, 1.00)
Requirement Permits & Approval: WRPA =(0.03, 0.73, 0.24)T				Pollutions and Safety Rules: WPSR =(0, 0.97, 0.03)T			

Table 7 (*Continued*)

Vague/incomplete Design Scope: WVDS = (0.34, 0.66, 0)T			
	Time	Cost	Quality
	Time	Cost	Quality
Time	(1.00, 1.00, 1.00)	(0.25,0.29,0.34)	(0.22,0.25,0.28)
Cost	(3.18, 3.68, 4.18)	(1.00, 1.00, 1.00)	(0.26,0.30,0.35)
Quality	(3.51,4.32,4.94)	(3.20,3.45,4.12)	(1.00, 1.00, 1.00)

Errors and Omissions: WEO =(0.20, 0.62, 0.18)T			
	Time	Cost	Quality
	Time	Cost	Quality
Time	(1.00, 1.00, 1.00)	(0.06,0.10,0.17)	(0.06,0.15,0.18)
Cost	(4.06,4.56,5.06)	(1.00, 1.00, 1.00)	(0.11,0.16,0.20)
Quality	(5.82,6.32,6.82)	(4.13, 4.56,5.06)	(1.00, 1.00, 1.00)

Labor Dispute and Strike: WLDS =(0, 0.40, 0.60)T			
	Time	Cost	Quality
Time	(1.00, 1.00, 1.00)	(0.31,0.39,0.44)	(0.32,0.39,0.48)
Cost	(3.18, 3.68, 4.18)	(1.00, 1.00, 1.00)	(0.30, 0.33,0.36)
Quality	(4.13, 4.56,5.06)	(4.35,4.56,5.06)	(1.00, 1.00, 1.00)

Defective Work: WDW =(0.05, 0.95, 0)T			
	Time	Cost	Quality
Time	(1.00, 1.00, 1.00)	(0.04,0.09,0.15)	(0.10,0.11,0.17)
Cost	(7.44,7.56,8.06)	(1.00, 1.00, 1.00)	(0.20,0.25,0.30)
Quality	(8.12,8.32,8.94)	(7.46,7.85,8.02)	(1.00, 1.00, 1.00)

Damage to Equipment: WDE =(0, 1, 0)T			
	Time	Cost	Quality
Time	(1.00, 1.00, 1.00)	(0.25,0.29,0.34)	(0.22,0.25,0.28)
Cost	(5.54, 5.64, 6.18)	(1.00, 1.00, 1.00)	(0.26,0.30,0.35)
Quality	(4.82,5.32,5.82)	(6.06,6.56,7.06)	(1.00, 1.00, 1.00)

Labor Productivity: WLP =(0, 0, 1)T			
	Time	Cost	Quality
Time	(1.00, 1.00, 1.00)	(0.25,0.29,0.34)	(0.22,0.25,0.28)
Cost	(3.18, 3.68, 4.18)	(1.00, 1.00, 1.00)	(0.26,0.30,0.35)
Quality	(3.51,4.32,4.94)	(3.20,3.45,4.12)	(1.00, 1.00, 1.00)

Labor Injuries: WLI =(0.46, 0.54, 0)T			
	Time	Cost	Quality
Time	(1.00, 1.00, 1.00)	(0.04,0.09,0.15)	(0.08,0.11,0.13)
Cost	(7.44,7.56,8.06)	(1.00, 1.00, 1.00)	(0.20,0.25,0.30)
Quality	(8.23,8.32,9.94)	(7.20,7.45,8.12)	(1.00, 1.00, 1.00)

Table 8. (Level 3) Matrices of pairwise comparisons and respective normalized weigh vectors

Design: $W_D = (0.67, 0.33)^T$

	Vague/incomplete Design scope	Errors and omissions
Vague/ incomplete Design scope	(1.00, 1.00, 1.00)	(5.06,5.54,6.13)
	(5.06,5.54,6.13)	(1.00, 1.00, 1.00)

Nature: $W_N = (0.63, 0.15, 0.22)^T$

	Weather	Landslide	Wind damage
Weather	(1.00, 1.00, 1.00)	(0.45,0.39,0.34)	(0.22,0.25,0.28)
Landslide	(4.18, 4.68, 5.18)	(1.00, 1.00, 1.00)	(0.26,0.30,0.35)
Wind damage	(3.82,4.32,4.82)	(3.06,3.56,4.06)	(1.00, 1.00, 1.00)

Political and Environmental: $W_{PE} = (0.43, 0.37, 0.20)^T$

	Change in laws and regulations	Requirement for permits and their approval	Pollutions and safety rules
Change in laws and regulations	1.00, 1.00, 1.00	0.13,0.16,0.22	0.25,0.27,0.35
Requirement for permits and their approval	3.24, 3.78, 4.26	1.00, 1.00, 1.00	0.26,0.33,0.37
Pollutions and safety rules	3.89,4.22,4.78	3.22,3.75,4.18	1.00, 1.00, 1.00

Financial and Economic: $W_{FE} = (0.19, 0.04, 0.15, 0.05, 0.57)^T$

	Inflation	Availability of funds from client	Changes in local law	Changes in govt. policy	Improper estimate
Inflation	1.00,1.00,1.00	0.16,0.21,0.25	0.18,0.20,0.27	0.17,0.21,0.28	0.22,0.27,0.33
Availability of funds from client	5.03,5.25,6.26	1.00,1.00,1.00	0.26,0.31,0.32	0.10,0.15,0.22	0.13,0.15,0.18
Changes in local law	5.15,5.36,6.24	6.32,6.46,6.88	1.00,1.00,1.00	0.19,0.22,0.23	0.21,0.33,0.35
Changes in govt. policy	6.45,7.16,7.83	6.22,6.46,6.84	5.17,5.56,6.67	1.00,1.00,1.00	0.19,0.26,0.30
Improper estimate	6.64,7.25,7.46	6.45,7.16,7.83	5.82,6.32,6.82	5.15,5.36,6.24	1.00,1.00,1.00

Job Site-related: $W_{JS} = (0.20, 0.08, 0.11, 0.07, 0.64)^T$

	Labour dispute and strike	Defective work	Damage to equipment	Labour productivity	Labour injuries
Labour dispute and strike	1.00,1.00,1.00	0.16,0.21,0.25	0.18,0.20,0.27	0.17,0.21,0.28	0.22,0.27,0.33
Defective work	5.03,5.25,6.26	1.00,1.00,1.00	0.26,0.31,0.32	0.10,0.15,0.22	0.13,0.15,0.18
Damage to equipment	5.15,5.36,6.24	6.32,6.46,6.88	1.00,1.00,1.00	0.19,0.22,0.23	0.21,0.33,0.35
Labour productivity	6.45,7.16,7.83	6.22,6.46,6.84	5.17,5.56,6.67	1.00,1.00,1.00	0.19,0.26,0.30
Labour injuries	6.64,7.25,7.46	6.45,7.16,7.83	5.82,6.32,6.82	5.15,5.36,6.24	1.00,1.00,1.00

Table 9. (Level 2) Matrices of pairwise comparisons and respective normalized weigh vectors

Risk Likelihood: $W_{RL} = (0.42,0.29,0.10,0.07,0.12)^T$					
	Design	Nature	Financial and economic	Political and environmental	Job site-related
Design	(1.00,1.00,1.00)	(0.35,0.41,0.44)	(0.37,0.40,0.46)	(0.31,0.38,0.44)	(0.30,0.37,0.42)
Nature	(5.15,5.36,6.24)	(1.00,1.00,1.00)	(0.26,0.31,0.32)	(0.30,0.33,0.40)	(0.33,0.35,0.38)
Financial and economic	(5.17,5.56,6.67)	(5.03,5.25,6.26)	(1.00,1.00,1.00)	(0.29,0.33,0.38)	(0.31,0.33,0.38)
Political & environmental	(5.22,5.12,5.82)	(6.22,6.46,6.84)	(5.15,5.36,6.24)	(1.00,1.00,1.00)	(0.29,0.36,0.38)
Job site-related	(5.12,5.33,6.77)	(6.45,7.16,7.83)	(5.82,6.32,6.82)	(5.11,5.24,6.26)	(1.00,1.00,1.00)
Risk Severity: $W_{RS} = (0.21, 0.19, 0.10, 0.05, 0.45)^T$					
	Design	Nature	Financial and economic	Political and environmental	Job site-related
Design	(1.00,1.00,1.00)	(0.16,0.21,0.25)	(0.04,0.10,0.14)	(0.17,0.21,0.28)	(0.22,0.27,0.33)
Nature	(5.03,5.25,6.26)	(1.00,1.00,1.00)	(0.06,0.12,0.16)	(0.10,0.15,0.22)	(0.13,0.15,0.18)
Financial and economic	(5.11,5.24,6.26)	(6.32,6.46,6.88)	(1.00,1.00,1.00)	(0.17,0.22,0.22)	(0.21,0.26,0.29)
Political & environmental	(6.45,7.16,7.83)	(6.22,6.46,6.84)	(5.17,5.56,6.67)	(1.00,1.00,1.00)	(0.19,0.26,0.30)
Job site-related	(6.64,7.25,7.46)	(6.66,7.34,7.78)	(5.22,5.12,5.82)	(5.15,5.36,6.24)	(1.00,1.00,1.00)

followed by two risk parameters, namely: risk likelihood and risk severity that located at the second level. The third and fourth levels are where all the identified risks situated. The lowest level presents the project objectives including time, cost, and quality. In this Pilot Run project, the risk assessment team identified five critical risk factors: Design, Nature, Financial & Economic, Political & Environment, and Job site-related. Under these five main factors, there are eighteen sub-factors as listed in Figure 4.

6.3. Pilot Run: pairwise comparison using fuzzy scale

In this step, pairwise comparison for every criterion was conducted at all these 5 levels in the hierarchy structure. Triangular fuzzy numbers (TFNs) in the pairwise comparison scale were used to determine the priorities of different criteria. Table 5 demonstrates the pairwise comparison results on determining the relative importance weighs for criteria with respect to "Weather" at level 4.

6.4. Pilot Run: aggregation of individual TFNs into group TFN

In this step, the contribution factor of each expert was multiplied with the corresponding individual TFNs.

Table 10. (Level 1) Matrices of pairwise comparisons and respective normalized weigh vectors

Construction Risks: $W_N = (0.57, 0.43)^T$		
	Risk likelihood	Risk severity
Risk likelihood	(1.00, 1.00, 1.00)	(0.16,0.29,0.31)
Risk severity	(4.18, 4.68, 5.18)	(1.00, 1.00, 1.00)

All the individual TFNs were aggregated into the group TFN. The aggregation score of each criterion was calculated using Eqs (3), (4), and (6). For instance, the aggregation score of "Cost and Time" under "Weather" was calculated as (3.18, 3.68, 4.18) as shown in Eq. (17). The aggregated scores for other criteria were obtained in the same way. Once the aggregation process was completed, the fuzzy comparison matrix of the criteria was produced as shown in Table 6:

$$\begin{aligned} S^{*}_{\text{cost \& time}} &= (5/2, 3, 7/2) \otimes 0.22 \otimes (9/2, 5, 11/2) \\ &\quad \otimes 0.34 \oplus (5/2, 3, 7/2) \otimes 0.16 \\ &\quad \oplus (5/2, 3, 7/2) \otimes 0.28 \\ &= (3.18, 3.68, 4.18). \end{aligned} \tag{17}$$

6.5. Pilot Run: calculated priority weighs using FSA

The priority weighs of the criteria were computed using FSA. From Table 6, the value of fuzzy synthetic extent with respect to each criterion was calculated using Eq. (8). The results are:

$$\begin{aligned} S_{Time} &= (1.47,\ 1.54,\ 1.62) \otimes \frac{1}{17.03} + \frac{1}{15.04} + \frac{1}{17.93} \\ &= (0.09,\ 0.10,\ 0.12); \\ S_{Cost} &= (4.44,\ 4.98,\ 5.53) \otimes \frac{1}{17.03} + \frac{1}{15.04} + \frac{1}{17.93} \\ &= (0.26,\ 0.32,\ 0.40); \\ S_{Quality} &= (7.88,\ 8.88,\ 9.98) \otimes \frac{1}{17.03} + \frac{1}{15.04} + \frac{1}{17.39} \\ &= (0.46,\ 0.58,\ 0.72). \end{aligned}$$

Table 11. Combination of priority weighs

Sub-criteria: **Design**

	Vague/incompleteDesign scope	Errors and omissions	Alternative priority weigh
Weigh	0.67	0.33	
Time	0.34	0.20	0.30
Cost	0.66	0.62	0.64
Quality	0	0.18	0.06

Sub-criteria: **Nature**

	Weather	Landslide	Wind damage	Alternative priority weigh
Weigh	0.63	0.15	0.22	
Time	0	0.13	0	0.10
Cost	0.50	0.48	1	0.53
Quality	0.50	0.39	0	0.37

Sub-criteria: **Financial and Economic**

	Inflation	Available of fund from client	Changes in local law	Changes in govt. policy	Improper estimate	Alternative priority weigh
Weigh	0.19	0.04	0.15	0.05	0.57	
Time	0	0.05	0	1	0.03	0.07
Cost	0.40	0.58	1	0	0.81	0.71
Quality	0.60	0.37	0	0	0.16	0.22

Sub-criteria: **Political and Environmental**

	Changes in laws and regulations	Requirement for permits and their approval	Pollutions and safety rules	Alternative priority weigh
Weigh	0.43	0.37	0.20	
Time	0.46	0.03	0	0.21
Cost	0.54	0.73	0.97	0.69

Table 11 (*Continued*)

Sub-criteria: **Design**

	Vague/incompleteDesign scope	Errors and omissions	Alternative priority weigh	
Quality	0	0.24	0.03	0.10

Sub-criteria: **Job Site-related**

	Labour dispute and strike	Defective work	Damage to equipment	Labour productivity	Labour injuries	Alternative priority weigh
Weigh	0.20	0.08	0.11	0.07	0.64	
Time	0	0.05	0	0	0.46	0.30
Cost	0.40	0.95	1	0	0.54	0.51
Quality	0.60	0	0	1	0	0.19

Sub-criteria: **Risk Likelihood**

	Design	Nature	Financial and economic	Political and environmental	Job site-related	Alternative priority weigh
Weigh	0.42	0.29	0.10	0.07	0.12	
Time	0.30	0.10	0.07	0.21	0.30	0.21
Cost	0.64	0.53	0.71	0.69	0.51	0.61
Quality	0.06	0.37	0.22	0.10	0.19	0.18

Sub-criteria: **Risk Severity**

	Design	Nature	Financial and economic	Political and environmental	Job site-related	Alternative priority weigh
Weigh	0.21	0.19	0.10	0.05	0.45	
Time	0.30	0.10	0.07	0.21	0.30	0.23
Cost	0.64	0.53	0.71	0.69	0.51	0.58
Quality	0.06	0.37	0.22	0.10	0.19	0.19

Main criteria: Construction risks

	Risk likelihood	Risk severity	Alternative priority weigh
Weigh	0.57	0.43	
Time	0.21	0.23	0.22
Cost	0.61	0.58	0.60
Quality	0.18	0.19	0.18

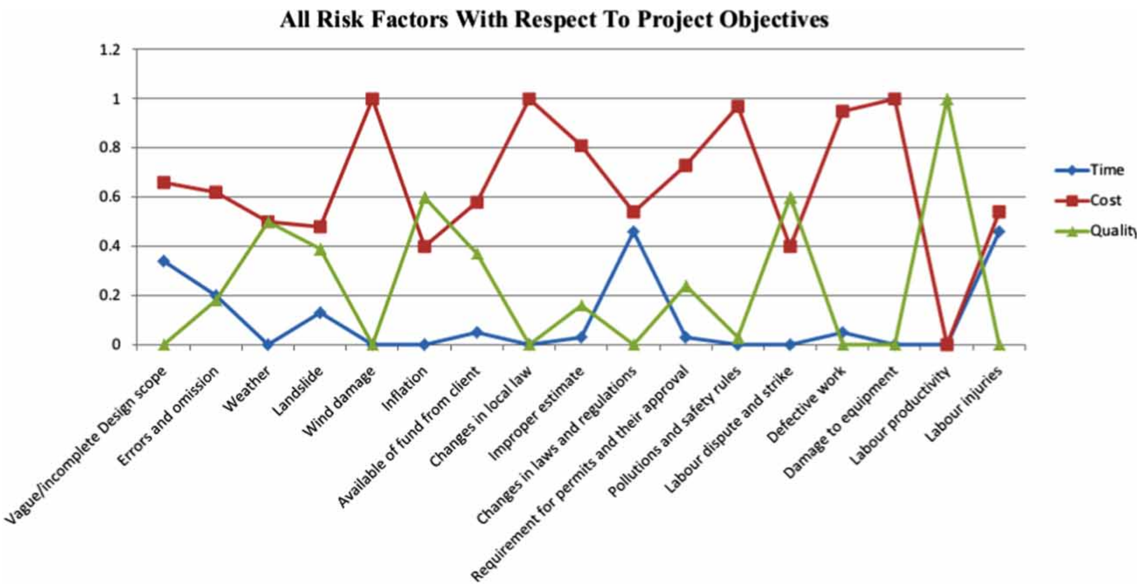

Fig. 5. All risk factors with respect to time, cost, and quality

Using these vectors, Eqs (9) to (12) were used to obtain the degree of possibility. The results are:

$$V(S_{Time} \geq S_{Cost}) = 0;$$
$$V\left(S_{Time} \geq S_{Quality}\right) = 0;$$
$$V(S_{Cost} \geq S_{Time}) = 1;$$
$$V\left(S_{Cost} \geq S_{Quality}\right) = 1;$$
$$V\left(S_{Quality} \geq S_{Time}\right) = 1;$$
$$V\left(S_{Quality} \geq S_{Cost}\right) = 1.$$

Similarly, using Eq. (13), the results were calculated as:

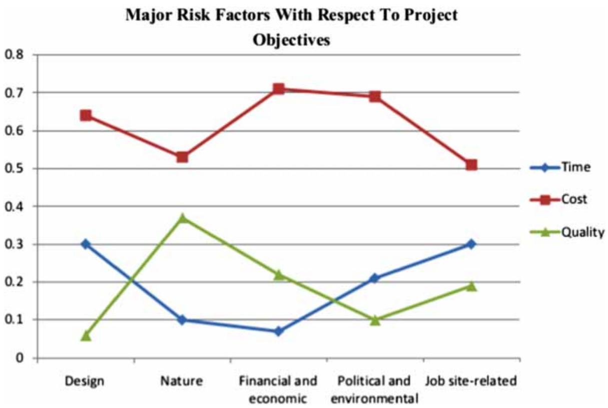

Fig. 6. Major risk factors with respect to time, cost, and quality

$$V\left(S_{Time} \geq S_{Cost,}S_{Quality}\right) = V\left(S_{Time} \geq S_{Cost} \text{ and } S_{Time} \geq S_{Quality}\right) = 0;$$
$$V\left(S_{Cost} \geq S_{Time,}S_{Quality}\right) = V\left(S_{Cost} \geq S_{Time} \text{ and } S_{Cost} \geq S_{Quality}\right) = 1;$$
$$V\left(S_{Quality} \geq S_{Time}, S_{Cost}\right) = V\left(S_{Quality} \geq S_{Cost} \text{ and } S_{Quality} \geq S_{Cost}\right) = 1.$$

Given by Eqs (14) and (15), the weigh vector is $W_w{}' = (0, 1, 1)^T$. Finally, via normalization of $W_w{}'$, the normalized weigh vector from Table 6 was calculated by using Eq. (16) as $W_w = (0, 0.5, 0.5)^T$, where W_w are non-fuzzy numbers. This step was repeated for each criterion at each level in the hierarchy tree to derive their normalized weigh vectors. The matrices of pairwise comparisons and their respective normalized weigh vector at level 4, level 3, level 2, and level 1 are presented in Tables 7, 8, 9, and 10, respectively.

6.6. Pilot Run: synthesized final results

Finally, the combination of priority weighs for each criterion at all levels were computed to determine overall priority weighs for the risks with respect to time, cost, and quality. The synthesized results are given in Table 11. The graphic results as shown in Figs 5 and 6 indicate that the project has higher risk in cost than in time and quality. Mitigation plan could then be executed to monitor and to control those risks with a high ranking to ensure their accordance with project objectives.

Table 12. Validation results of FSM

Evaluator	Flexibility	Accessibility	Completeness	Reliability	User Friendly	Assistance in Decision-making	Adaptability for complexity
A	7	8	8	9	9	10	10
B	9	8	7	8	9	9	9
C	8	7	8	10	10	9	10
D	8	7	9	8	9	8	9
E	7	8	9	10	10	10	10
F	7	7	9	9	10	9	10
G	9	9	8	9	9	9	10
H	8	7	7	8	9	10	9
I	8	8	9	10	9	9	10
MEAN	**7.9**	**7.7**	**8.2**	**9.0**	**9.3**	**9.2**	**9.7**

6.7. Validation of FSM

A validation process of the developed FSM was carried out to determine whether this model was of application value for risk evaluation in construction practices, which was conducted online by randomly selected 9 practitioners in the construction sector worldwide. Each parameter was given a 10-scale evaluation. The validation results as shown in Table 12 indicate that the developed FSM could systematically help practitioners to evaluate construction risks. The values of flexibility, accessibility, completeness, reliability, user friendly level, assistance in decision-making, and adaptability for complexity are acceptable.

7. Benefits and limitations

The advantage of a Fuzzy-AHP model is that it could efficiently quantify the valuable subjective data to cope with multiple contradicting risk problems. Taking project objectives such as time, cost, and quality into consideration are very important in the risk assessment process. As to guarantee project success, it entails effective risk management of a project. Compared with those existing methods, the FSM developed in this study has the following benefits: a) it accelerates the decision-making process. Construction practitioners could conduct a complicated risk assessment process effectively using the developed model which is simple and systematic in evaluation and computation; b) it gives more convincing result with the consideration of project objectives within the framework, hence it aids in an optimal allocation of project resources to mitigate possible risks detrimental to the success of a project in terms of time, cost, and quality; c) it is able to capture the vagueness of human thinking style and to ensure the consistency in multi-criteria decision-making process; and d) it could be used in measuring risks across different stages of a project life cycle, from the inception till the completion of a project. Nevertheless, the developed FSM has a shortcoming that the computational fuzzy calculations in this model are rather time-consuming, which needs to be optimized in future study.

8. Conclusions and recommendations

Aiming to remove complex and unreliable process arising in subjective judgments during construction risk assessments, the developed FSM provides an appropriate approach to tackle the fuzziness involved in the decision-making process. The pilot run revealed that the FSM could accelerate the decision-making process and could provide optimal allocation of project resources to mitigate possible risks detrimental to the success of a project in terms of time, cost, and quality. Further efforts are recommended in developing a decision support tool to conduct the tedious fuzzy calculations to facilitate the overall risk assessment process. Besides, since the computational fuzzy calculations in the developed model is rather time-consuming, the simplification and the optimization of the fuzzy calculation process should be paid attention to in future research works.

References

Ahmed, A.; Kayis, B.; Amornsawadwatana, S. 2007. A review of techniques for risk management in projects, *Benchmarking: an International Journal* 14(1): 22–36. http://dx.doi.org/10.1108/14635770710730919.

An, M.; Baker, C.; Zeng, J. 2005. A fuzzy-logic-based approach to qualitative risk modelling in the construction process, *World Journal of Engineering* 2(1): 1–12.

Baccarini, D.; Archer, R. 2001. The risk ranking of projects: a methodology, *International Journal of Project Management* 19(3): 139–145. http://dx.doi.org/10.1016/S0263-7863(99)00074-5.

Baloi, D.; Price, A. D. F. 2003. Modelling global risk factors affecting construction cost performance, *International Journal of Project Management* 21(4): 261–269. http://dx.doi.org/10.1016/S0263-7863(02)00017-0.

Berkeley, D.; Humphreys, P. C.; Thomas, R. D. 1991. Project risk action management, *Construction Management and Economics* 9(1): 3–17. http://dx.doi.org/10.1080/01446199100000002.

Bojadziev, G.; Bojadziev, M. 2007. *Fuzzy logic for business, finance, and management*. 2nd ed. Singapore: World Scientific. 232 p.

Buckley, J. J. 1985. Fuzzy hierarchical analysis, *Fuzzy Sets and Systems* 17(3): 233–247. http://dx.doi.org/10.1016/0165-0114(85)90090-9.

Cagno, E.; Caron, F.; Mancini, M. 2007. A multi-dimensional analysis of major risks in complex projects, *Risk Management* 9: 1–18. http://dx.doi.org/10.1057/palgrave.rm.8250014.

Chan, F. T. S.; Kumar, N. 2007. Global supplier development considering risk factors using fuzzy extended AHP-based approach, *Omega* 35(4): 417–431. http://dx.doi.org/10.1016/j.omega.2005.08.004.

Chang, D. Y. 1992. *Extent Analysis and Synthetic Decision, Optimization Techniques and Applications.* Vol. 1. Singapore: World Scientific.

Chang, D.-Y. 1996. Applications of the extent analysis method on Fuzzy-AHP, *European Journal of Operational Research* 95(3): 649–655. http://dx.doi.org/10.1016/0377-2217(95)00300-2.

Chang, Y.-H.; Yeh, C.-H.; Wang, S.-Y. 2007. A survey and optimization-based evaluation of development strategies for the air cargo industry, *International Journal of Production Economics* 106(2): 550–562. http://dx.doi.org/10.1016/j.ijpe.2006.06.016.

Chang, Y.-H.; Yeh, C.-H. 2002. A survey analysis of service quality for domestic airlines, *European Journal of Operational Research* 139(1): 166–177. http://dx.doi.org/10.1016/S0377-2217(01)00148-5.

Chapman, C. B.; Cooper, D. F. 1983. Risk analysis: testing some prejudices, *European Journal of Operational Research* 14(1): 238–247. http://dx.doi.org/10.1016/0377-2217(83)90260-6.

Chen, C.-T.; Huang, S.-F. 2006. Order-fulfilment ability analysis in the supply-chain system with fuzzy operation times, *International Journal Production Economics* 101(1): 185–193. http://dx.doi.org/10.1016/j.ijpe.2005.05.003.

Chen, S.-P.; Hsueh, Y.-J. 2007. A simple approach to fuzzy critical path analysis in project networks, *Applied Mathematical Modelling* 32(7): 1289–1297. http://dx.doi.org/10.1016/j.apm.2007.04.009.

Chen, S.-M. 2001. Fuzzy group decision making for evaluating the rate of aggregative risk in software development, *Fuzzy Sets and Systems* 118(1): 75–88. http://dx.doi.org/10.1016/S0165-0114(99)00103-7.

Cheng, M.-Y.; Tsai, H.-C.; Sudjono, E. 2010. Evolutionary fuzzy hybrid neural network for project cash flow control, *Engineering Applications of Artificial Intelligence* 23(4): 604–613. http://dx.doi.org/10.1016/j.engappai.2009.10.003.

Cho, H.-M.; Choi, H.-H.; Kim, Y.-K. 2002. A risk assessment methodology for incorporating uncertainties using fuzzy concepts, *Reliability Engineering & System Safety* 78(2): 173–183. http://dx.doi.org/10.1016/S0951-8320(02)00158-8.

Choi, H.-H.; Cho, H.-N.; Seo, J. W. 2004. Risk assessment methodology for underground construction projects, *Journal of Construction Engineering and Management* ASCE 130(2): 258–272. http://dx.doi.org/10.1061/(ASCE)0733-9364(2004)130:2(258).

Chun, M.-H.; Ahn, K.-II. 1992. Assessment of the potential application of fuzzy set theory to accident progression event trees with phenomenological uncertainties, *Reliability Engineering & System Safety* 37(3): 237–252. http://dx.doi.org/10.1016/0951-8320(92)90130-D.

Cioffi, D. F.; Khamooshi, H. 2009. A practical method of determining project risk contingency budgets, *Journal of the Operational Research Society* 60: 565–571. http://dx.doi.org/10.1057/palgrave.jors.2602586.

Cooper, D. F.; Chapman, C. B. 1987. *Risk analysis for large projects: models, methods, and cases.* New York: John Willey. 260 p.

Cooper, D. F.; MacDonald, D. H.; Chapman, C. B. 1985. Risk analysis of a construction cost estimate, *International Journal of Project Management* 3(3): 141–149. http://dx.doi.org/10.1016/0263-7863(85)90065-1.

Dağdeviren, M.; Yüksel, I. 2008. Developing a fuzzy analytic hierarchy process model for behaviour-based safety management, *Information Sciences* 178(6): 1717–1733. http://dx.doi.org/10.1016/j.ins.2007.10.016.

Dey, P.; Tabucanon, M. T.; Ogunlana, S. 1994. Planning for project control through risk analysis: a petroleum pipeline-laying project, *International Journal of Project Management* 12(1): 23–33. http://dx.doi.org/10.1016/0263-7863(94)90006-X.

Dey, P. K. 2001. Decision support system for risk management: a case study, *Management Decision* 39(8): 634–649. http://dx.doi.org/10.1108/00251740110399558.

Diekmann, J. E. 1992. Risk analysis: lessons from artificial intelligence, *International Journal of Project Management* 10(2): 75–80. http://dx.doi.org/10.1016/0263-7863(92)90059-I.

Dikmen, I.; Birgonul, M. T.; Gur, K. 2007a. A case-based decision support tool for bid mark-up estimation of international construction projects, *Automation in Construction* 17(1): 30–44. http://dx.doi.org/10.1016/j.autcon.2007.02.009.

Dikmen, I.; Birgonul, M. T.; Han, S. 2007b. Using fuzzy risk assessment to rate cost overrun risk in international construction projects, *International Journal of Project Management* 25(5): 494–505. http://dx.doi.org/10.1016/j.ijproman.2006.12.002.

Ding, J.-F.; Liang, G.-S. 2005. Using fuzzy MCDM to select partners of strategic alliances for liner shipping, *Information Sciences* 173(1–3): 197–225. http://dx.doi.org/10.1016/j.ins.2004.07.013.

Dweiri, F. T.; Kablan, M. M. 2006. Using fuzzy decision making for the evaluation of the project management internal efficiency, *Decision Support Systems* 42(2): 712–726. http://dx.doi.org/10.1016/j.dss.2005.04.001.

Flanagan, R.; Norman, G. 1993. *Risk management and construction*. Victoria, Australia: Blackwell Science Pty Ltd. 224 p.

Franceschini, F.; Galleto, M. 2001. A new approach for evaluation of risk priorities of failure modes in FMEA, *International Journal of Production Research* 39(13): 2991–3002. http://dx.doi.org/10.1080/00207540110056162

Han, S. H.; Kim, D. Y.; Kim, H.; Jang, W.-S. 2008. A web-based integrated system for international project risk management, *Automation in Construction* 17(3): 342–356. http://dx.doi.org/10.1016/j.autcon.2007.05.012.

Hastak, M.; Shaked, A. 2000. ICRAM-1: model for international construction risk assessment, *Journal of Management in Engineering* ASCE 16(1): 59–69. http://dx.doi.org/10.1061/(ASCE)0742-597X(2000)16:1(59).

Heshmaty, B.; Kandel, A. 1985. Fuzzy linear regression and its applications to forecasting in uncertain environment, *Fuzzy Sets and Systems* 15(2): 159–191. http://dx.doi.org/10.1016/0165-0114(85)90044-2.

Huang, D.; Chen, T.; Wang, M.-J. J. 2001. A fuzzy set approach for event tree analysis, *Fuzzy Sets and Systems* 118(1): 153–165. http://dx.doi.org/10.1016/S0165-0114(98)00288-7.

Idrus, A.; Nuruddin, M. F.; Rohman, M. A. 2011. Development of project cost contingency estimation model using risk analysis and fuzzy expert system, *Expert Systems with Applications* 38(3): 1501–1508. http://dx.doi.org/10.1016/j.eswa.2010.07.061.

Jannadi, O. A.; Almishari, S. 2003. Risk assessment in construction, *Journal of Construction Engineering and Management* 129(5): 492–500. http://dx.doi.org/10.1061/(ASCE)0733-9364(2003)129:5(492).

Kahraman, C.; Cebeci, U.; Ruan, D. 2004. Multi-attribute comparison of catering service companies using Fuzzy-AHP: the case of Turkey, *International Journal of Production Economics* 87(2): 171–184. http://dx.doi.org/10.1016/S0925-5273(03)00099-9.

Kangari, R.; Riggs, L. S. 1989. Construction risk assessment by linguistics, *IEEE Transitions on Engineering Management* 36(2): 126–131. http://dx.doi.org/10.1109/17.18829.

Karsak, E. E.; Tolga, E. 2001. Fuzzy multi-criteria decision-making procedure for evaluating advanced manufacturing system investments, *International Journal of Production Economics* 69(1): 49–64.

Kasabov, N. K. 1996. *Foundation of neural network: fuzzy systems and knowledge engineering*. MIT Press. 568 p.

Latham, M. 1994. Constructing the Team, *Final Report of the Government/Industry Review of Procurement and Contractual Arrangements in The UK Construction Industry*. London: HMSO. 140 p.

Lee, H. M.; Lin, L. 2010. A new fuzzy risk assessment approach, in *Proc. of Knowledge-Based and Intelligent Information and Engineering Systems: 14th International Conference, KES 2010*, 8–10 September, 2010, Cardiff, UK, 98–105.

Lyons, T.; Skitmore, M. 2004. Project risk management in the Queensland engineering construction industry: a survey, *International Journal of Project Management* 22(1): 51–61.

Mustafa, M. A.; Al-Bahar, J. F. 1991. Project risk analytic assessment using the Hierarchy Process, *IEEE Transactions on Engineering Management* 38(1): 46–52.

Mulholland, B.; Christian, J. 1999. Risk assessment in construction schedules, *Journal of Construction Engineering and Management* ASCE 125(1): 8–15.

Nieto-Morote, A.; Ruz-Vila, F. 2011. A fuzzy approach to construction project risk assessment, *International Journal of Project Management* 29(2): 220–231.

Naeni, L. M.; Shadrokh, S.; Salehipour, A. 2011. A fuzzy approach for the earned value management, *International Journal of Project Management* 29(6): 764–772.

Negnevitsky, M. 2004. *Artificial intelligence: a guide to intelligent systems*. 2nd ed. London, UK: Addison-Wesley. 440 p.

Nguyen, V. U. 1985. Tender evaluation by fuzzy sets, *Journal of Construction Engineering and Management* ASCE 111(3): 231–243.

Paek, J. H.; Lee, Y. W.; Ock, J. H. 1993. Pricing construction risks: fuzzy set theory, *Journal of Construction Engineering and Management* ASCE 119(4): 743–756.

Pedrycz, W. 1994. Why triangular membership functions? *Fuzzy Sets and Systems* 64(1): 21–30.

Riggs, J. L.; Brown, S. B.; Trueblood, R. B. 1994. Integration of technical, cost and schedule risks in project management, *Computers & Operations Research* 21(5): 521–533.

Saaty, T. L. 1980. *The analytic hierarchy process*. New York: McGraw-Hill. 281 p.

Saaty, T. L. 1990. How to make a decision: the analytic hierarchy process, *European Journal of Operational Research* 48(1): 9–26.

Shang, H.; Anumba, C. J.; Bouchlaghem, D. M.; Miles, J. C.; Cen, M.; Taylor, M. 2005. An intelligent risk assessment system for distributed construction teams, *Engineering, Construction and Architectural Management* 12(4): 391–409.

Sii, H. S.; Wang, J. 2003. A design-decision support framework for evaluation of design options/proposals using a composite structure methodology based on the approximate reasoning approach and reasoning method, in *Proc. of the Institution of Mechanical Engineers* 217(1): 59–76.

Sun, Y.; Huang, R.; Chen, D.; Li, H. 2008. Fuzzy Set-based risk evaluation model for real estate projects, *Tsinghua Science and Technology* 13(S1): 158–164.

Tah, J. H. M.; Carr, V. 2000. A proposal for construction project risk assessment using fuzzy logic, *Construction Management and Economics* 18(4): 491–500.

Tah, J. H. M.; Carr, V. 2001. Knowledge-Based approach to construction project risk management, *Journal of Computing in Civil Engineering* ASCE 15(3): 170–177.

Tavares, L. V.; Ferreira, J. A. A.; Coehlo, J. S. 1998. On the optimal management of project risk, *European Journal of Operational Research* 107: 415–469.

Thomas, A. V.; Kalidindi, S. N.; Ganesh, L. S. 2006. Modeling and assessment of critical risks in BOT road projects, *Construction Management and Economics* 24(4): 407–424.

van Laarhoven, P. J. M.; Pedrycz, W. 1983. A fuzzy extension of Saaty's priority theory, *Fuzzy Sets and Systems* 11(1–3): 199–227.

Wang, S. Q.; Dulaimi, M. F.; Aguria, M. Y. 2004. Risk management framework for construction projects in developing countries, *Construction Management and Economics* 22(3): 237–252.

Wang, Y.-M.; Elhag, T. M. S. 2007. A fuzzy group decision making approach for bridge risk assessment, *Computers & Industrial Engineering* 53(1): 137–148.

Ward, S.; Chapman, C. 2003. Transforming project risk management into project uncertainty management, *International Journal of Project Management* 21(2): 97–105.

Wei, C.-C.; Liang, G.-S.; Wang, M.-J. J. 2007. A comprehensive supply chain management project selection framework under fuzzy environment, *International Journal of Project Management* 25(6): 627–636.

Williams, T. M. 1995. A classified bibliography of recent research relating to project risk management, *European Journal of Operational Research* 85(1): 18–38.

Wirba, E. N.; Tah, J. H. M.; Howes, R. 1996. Risk interdependencies and natural language computations, *Engineering, Construction and Architectural Management* 3(4): 251–269.

Xu, Z.-S.; Chen, J. 2007. An interactive method for fuzzy multiple attribute group decision making, *Information Sciences* 177(1): 248–263.

Yager, R. R. 2002. Uncertainty representation using fuzzy measures, *IEEE Transactions on Systems, Man, and Cybernetics, Part B: Cybernetics* 32(1): 20–28.

Yeo, K. T. 1990. Risks, classification of estimates and contingency, *Journal of Management Engineering* 6(4): 458–470.

Zadeh, L. A. 1965. Fuzzy sets, *Information and Control* 8(3): 338–353.

Zadeh, L. A. 1978. Fuzzy sets as a basis for a theory of possibility, *Fuzzy Sets and Systems* 1(1): 3–28.

Zavadskas, E. K.; Turskis, Z.; Tamosaitiene, J. 2010. Risk assessment of construction projects, *Journal of Civil Engineering and Management* 16(1): 33–46.

Zayed, T.; Amer, M.; Pan, J. 2008. Assessing risk and uncertainty inherent in Chinese highway projects using AHP, *International Journal of Project Management* 26(4): 408–419.

Zeng, J.; An, M.; Smith, N. J. 2007. Application of a fuzzy based decision making methodology to construction project risk assessment, *International Journal of Project Management* 25(6): 589–600.

Zhang, H. 2007. A redefinition of the project risk process: using vulnerability to open up the event consequence link, *International Journal of Project Management* 25(7): 694–701.

Zhang, G.; Zou, P. X. 2007. Fuzzy analytical hierarchy process risk assessment approach for joint venture construction projects in China, *Journal of Construction Engineering and Management* ASCE 133(10): 771–779.

Zhang, H.; Dong, Y.; Li, M.; Sun, Z. 2002. Research for application of group decision method on appraisement system of science research schema, in *Proc. of the 4th World Congress on Intelligent Control and Automation*, 10–14 June, 2002, Shanghai, China, 602–606.

Zheng, D. X. M.; Ng, T. 2005. Stochastic time-cost optimization model incorporating fuzzy sets theory and non-replacement, *Journal of Constructing Engineering and Management* ASCE 131(2): 176–186.

Zhi, H. 1995. Risk management for overseas construction, *International Journal of Project Management* 13(4): 231–237.

Zieliński, P. 2005. On computing the latest starting times and floats of activities in a network with imprecise durations, *Fuzzy Sets Systems* 150(1): 53–76.

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