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ARTICLE

Risk identification and assessment for engineering procurement construction management projects using fuzzy set theory

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Abstract: Considerable work has been carried out on risk qualitative and quantitative assessment but far less on risk identification. This paper introduces a newly developed method for risk identification, based on micro risk breakdown structure and newly introduced identification procedure called preventive root cause and effective remedial. It also introduces a risk responsibility matrix that distributes the responsibilities associated with each risk among project stakeholders and introduces a newly developed method for qualitative and quantitative assessment of each item using fuzzy set and fuzzy probability theories. Output of the proposed assessment method is pre-mitigation contingency of each risk which represents a quantitative indicator for decision making whether to mitigate or not the risk being considered. Two case studies and one numerical example are presented to demonstrate the applicability and illustrate the essential features of proposed identification, allocation, and assessment methods.

Key words: risk, identification, assessment, ownership, EPCM, construction, fuzzy set, mitigation, contingency.

Résumé : Il y a eu un travail considérable effectué au sujet de l'évaluation qualitative et quantitative du risque, mais très peu sur l'identification de risques. Dans le cadre de cette étude, on présente une méthode d'identification de risques nouvellement développée, fondée sur une structure de répartition des risques au niveau micro et une procédure d'identification nouvellement mise en place appelée prévention de la cause fondamentale et correctif efficace. On présente aussi une matrice de la responsabilité des risques qui répartit les responsabilités associées à chaque risque entre les parties intéressées et présente une méthode nouvellement développée pour l'évaluation qualitative et quantitative de chaque élément en utilisant la théorie des ensembles flous et celle des probabilités floues. Les résultats de la méthode d'évaluation proposée indiquent la contingence de pré atténuation de chaque risque qui représente un indicateur quantitatif pour la prise de décision d'atténuer ou de ne pas atténuer le risque considéré. On présente deux études de cas et un exemple numérique afin de démontrer l'applicabilité des méthodes d'identification, de répartition et d'évaluation proposées et on en illustre les caractéristiques essentielles. [Traduit par la Rédaction]

Mots-clés : risque, identification, évaluation, attribution, gestion d'ingénierie-approvisionnement-construction (GIAC), construction, ensemble flou, atténuation, contingence.

Background

The risk identification process aims to identify risk items associated with a construction project, while risk allocation tends to assign the risk ownership to a member of the project team. Risk assessment represents the process that evaluates the probability of occurrence and the consequences of the risk being considered. However, any failure in risk assessment may generate cost overruns and project delays (Serpella et al. 2014). Reliable risk identification process should first be performed to ensure effective risk assessment (Tworek 2012; ISO 2009). Researchers introduced several methods for risk identification such as: checklists, documentation review (Deniz and Kaymak 2007), brainstorming (Chapman 2001), surveys (Bajaj et al. 1997), interviews (Chapman 2001), strength weakness opportunity threat (SWOT) analysis (Sweeting 2011), nominal group technique (Delbecq and VandeVen 1971), and Delphi technique (Chapman 1998). A study about effectiveness of these techniques results show that 68% of contractors use brainstorming technique, regardless of its limitations, to identify risks associated with construction projects (Tworek 2010). Fuzzy set based identification methods have been also introduced, which integrate fuzzy set theory (Zadeh 1965) with the analytic network process (Liu and Tsai 2012), root cause analysis (Abdelgawad and Fayek 2010), multi-criteria group decision making (Tavakkoli-Moghaddam et al. 2011), and what is referred to as macro approach (Borghesi and Gaudenzi 2013). However, existing identification techniques cannot, on their own, identify all risks and unfavorable events associated with a project or business (Borghesi and Gaudenzi 2013; Tworek 2010). Unidentified risk may be dangerous for one or more project objectives and may generate harmful consequences even before it can be addressed (Rounds and Segner 2011). Also, Loosemore et al. (2006) assert that a single unidentified risk may totally cripple a project or business.

By definition, risk allocation process assigns the risk being considered to a person or an entity that can better manage the risk (ISO 2009; PMI 2013). However, the common practice of risk allocation is to assign contractually the risk to a project party with minimum negotiation effort and least cost (Hanna et al. 2013).

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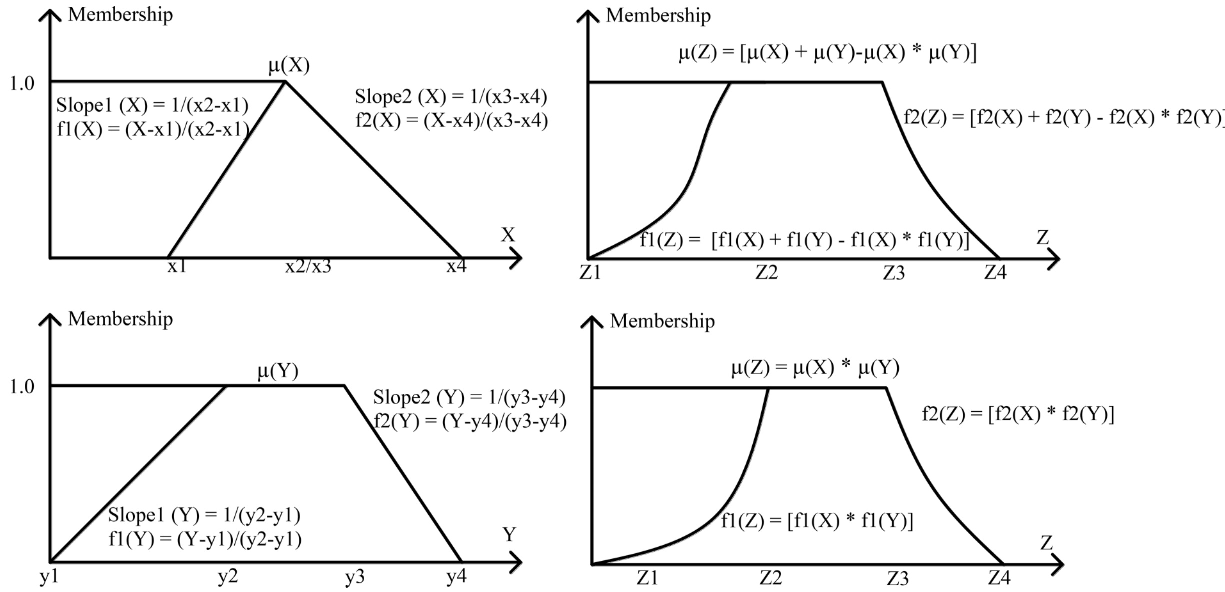
Fig. 1. Fuzzy membership function calculations.



This allocation practice is referred to by Hanna et al. (2013) as inappropriate risk allocation method. Also, Peckiene et al. (2013) described the contractual risk assignment as inequitable and unreasonable process.

Quantitative and qualitative risk assessment methods using fuzzy theory (Zadeh 1965) have been introduced. Researchers recommend the use of fuzzy theory because it is capable of modeling imprecision and ambiguity associated with input data (Carr and Tah 2001; Nieto-Morote and Ruz-Vila 2011). In addition to that, fuzzy theory is applicable regardless of the availability of historical data (Salah and Moselhi 2013). Several fuzzy set based methods have been introduced for qualitative risk assessment in the construction industry. However, the main limitations of these methods are: the use of a specific shape of fuzzy membership function (i.e., triangular) that represents the risk item (KarimiAzari et al. 2011), the complicated procedure that is applicable to a limited number of risks (Tamošaitienė et al. 2013; Lazzerini and Mkrtchyan 2011; KarimiAzari et al. 2011; Sadeghi et al. 2010; Zeng et al. 2007), and the need of historical data when a hybrid approach is used to integrate Monte-Carlo simulation with fuzzy set theory (Sadeghi et al. 2010). Also, several fuzzy set based methods have been introduced for quantitative risk assessment in the construction industry (Salah and Moselhi 2015; Zhao 2013; Aminbakhsh et al. 2013; Liu and Tsai 2012; Chan et al. 2011; Xu et al. 2010). However, the main limitations of these methods are: the disregard of uncertainty and fuzziness associated with the input from experts in respect to probability of occurrence and consequences (Chan et al. 2011; Xu et al. 2010), the use of macro approach (Zhao et al. 2013; Chan et al. 2011), and the use of triangular shape for fuzzy membership functions to represent the risk items (Zhao et al. 2013; Liu and Tsai 2012). The current practice of risk assessment utilizes different methods for qualitative and quantitative assessment, which may generate contradictory results.

Problem statement

The literature review reveals the need for: (1) comprehensive risk identification method that maximizes the identification rate of risk items associated with a construction project, (2) systematic risk allocation method that assigns each identified risk to a person or entity based on predetermined set of criteria, and (3) new risk assessment method that utilizes the fuzzy probability theory (Zadeh 2008).

Uncertainty modeling

By definition, a risk represents an uncertain event (PMI 2013). Fuzzy set theory (Zadeh 1965) and fuzzy probability theories (Zadeh 2008) were introduced to model the uncertainties associated with risk. Fuzzy membership calculations (Zadeh 1965) are used to generate the membership functions of added and multiplied fuzzy numbers, as shown in Fig. 1, using eqs. (1) and (2), respectively.

$$\mu_{\widetilde{A+B}} = \mu_{\tilde{A}} + \mu_{\tilde{B}} - \mu_{\tilde{A}} \times \mu_{\tilde{B}} \tag{1}$$

$$\mu_{\widetilde{A\times B}} = \mu_{\tilde{A}} \times \mu_{\tilde{B}} \tag{2}$$

where μ represents the membership function of a fuzzy number.

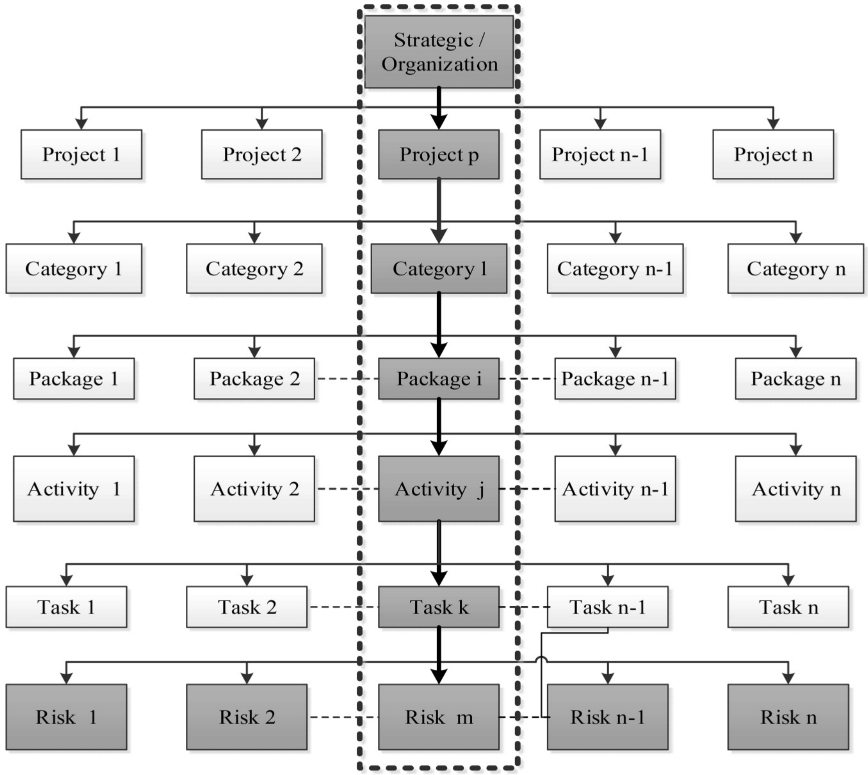
These membership functions are defuzzified using defuzzification methods (Nieto-Morote and Ruz-Vila 2011) such as: centre of area (COA), centre of sum (COS), centre of maximum (COM), and mean of maximum (MOM). All areas of a membership function "μ" are assumed to have the same importance factor and accordingly employed the centre of area defuzzification method as shown in eq. (3).

$$y^* = \frac{\int x\mu_i(x)}{\int \mu_i(x)} \tag{3}$$

Proposed identification method

The proposed risk identification method utilizes micro approach to identify known risks and majority of unknown risks associated with engineering procurement construction management (EPCM) projects. In this paper, known risks are defined as risks items that are identified and managed in previous projects, and unknown risks are those that are hidden or not yet identified. The proposed method introduces a new procedure for risk ownership allocation based on the "one risk, one owner" approach. However, since a risk may represent an exposure to all project stakeholders, this paper also introduces the risk responsibility matrix (RRM) that distributes the risk responsibilities among project stakeholders.

Fig. 2. Micro risk breakdown structure.



Data collection

Data gathering tools (e.g., documentation review) are utilized for data collection. Additional data can also be gathered from similar projects and past experience database such as: learned lessons and organizational process assets. Successful data collection, which includes data pertinent to work breakdown structure (WBS) and organization breakdown structure (OBS), eases the generation of micro risk breakdown structure (MRBS) which tends to enhance the identification rate of unknown risk items.

Micro risk breakdown structure

After data collection, a micro risk breakdown structure (MRBS) which breakdowns the project up to task level and identifies the risk associated with each task is generated as shown in Fig. 2. Thus, the use of a MRBS eases the identification of known risk items and increases the identification rate of unknown risk items because it focuses only on those associated with individual tasks. Similar to project WBS, the MRBS helps users to assign a unique identification number (UIDN) for each risk item using numbers of associated task, activity, package, category, and project. The number of levels in MRBS differs from project to project, therefore the UIDN that referred to a risk item associated with a certain project differs from the UIDN that refers to the same risk in other projects. However, a standardized UIDN, which represents the same risk in all the projects, can be reached if an organization uses a fixed number of levels in generating the MRBS (e.g., five levels).

Identification procedure

For each task, experts identify known risk items using one or more identification tools as shown in Fig. 3. The following six steps describe the developed identification procedure:

Step 1. Identification of known risk items using one or more of the identification techniques.

Step 2. Gathering of data from previous experience and learned lessons databases.

Step 3. Investigating the potentials for unknown risks by identifying undesirable situations that have been occurred (e.g., cost overrun) in previous projects.

Step 4. Utilizing the root cause analysis method to identify all the unknown risk items associated with the situations identified in step 3.

Step 5. Applying the cause-effect diagram method to identify the consequences of each unknown risk item identified in step 4.

Step 6. Combining the list of known and unknown risks to generate the register of risk items associated with each task.

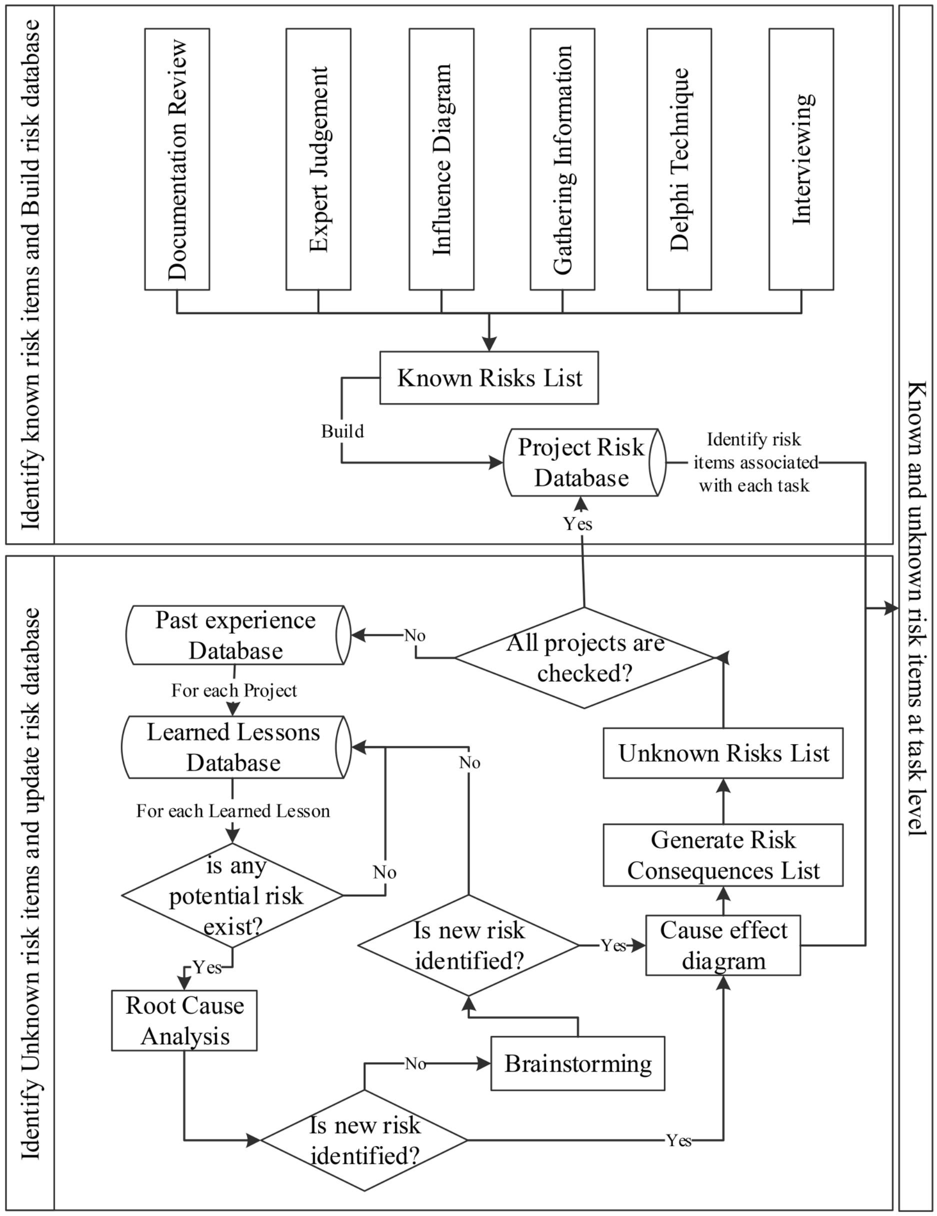
The proposed identification procedure uses a combination, rather than one only, of existing identification methods which may elevate the rate of identification for known and unknown risk items associated with each task. It also allows identification of the consequences of each risk item.

Risk ownership determination

Considering the definition of risk owner as "a person or entity that better manage the risk being considered" (ISO 2009), the proposed method introduces a new procedure for risk ownership determination. This procedure introduces the "one risk, one owner" approach which tends to allocate each risk to one owner only. This procedure includes two steps: (1) selection of risk owner and (2) generation of "risk responsibility matrix".

Risk owner is characterized by his capacity, effectiveness, and ability to manage the risk being considered (Risk Management Capabilities 2011). Capacity, effectiveness, and ability are defined respectively as maximum effort that can be handled, degree of successfulness in producing desired results, and possession of means and skills to do things. The determination of risk ownership is based on a score, denoted as risk ownership score (ROS), that combines the ability (Ab), capacity (Ca), and effectiveness (Ef) of each risk owner to effectively manage the risk being considered.

Fig. 3. Example of identification of risk items at task level.



In the ownership determination procedure, fuzzy indices are developed to measure the degree of satisfying, by each ownership candidate, the capacity (CaI), efficiency (EfI), and ability (AbI) to better manage the risk being considered. Then, the three indices are combined into a risk ownership score (ROS) using eq. (4). The fuzzy membership function of ROS is calculated also using fuzzy membership addition (eq. (2)) as presented in eq. (5). It should be noted that the fuzzy addition is selected to incorporate the extreme case when all indices are equal to 0.

$$(4)\qquad \widetilde{\mathrm{ROS}} = \widetilde{\mathrm{AbI}} + \widetilde{\mathrm{CaI}} + \widetilde{\mathrm{EfI}}$$

$$(5)\qquad 1 - \mu_{\widetilde{\mathrm{ROS}}} = (1 - \mu_{\widetilde{\mathrm{AbI}}}) \times (1 - \mu_{\widetilde{\mathrm{CaI}}}) \times (1 - \mu_{\widetilde{\mathrm{EfI}}})$$

where $\widetilde{\mathrm{ROS}}$, $\widetilde{\mathrm{AbI}}$, $\widetilde{\mathrm{CaI}}$, and $\widetilde{\mathrm{EfI}}$ represent risk ownership, ability, capacity, and efficiency indices; $\mu_{\widetilde{\mathrm{ROS}}}$, $\mu_{\widetilde{\mathrm{AbI}}}$, $\mu_{\widetilde{\mathrm{CaI}}}$, and $\mu_{\widetilde{\mathrm{EfI}}}$ represent the membership functions of risk ownership, ability, capacity, and efficiency indices.

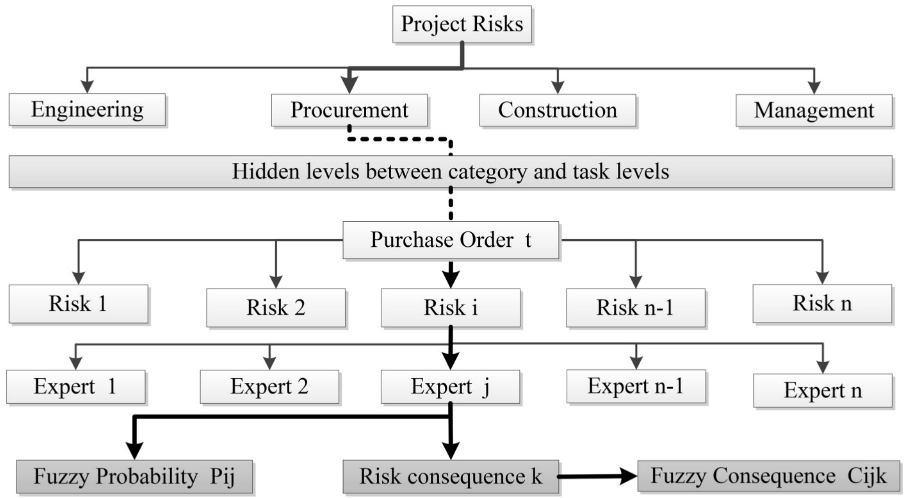
Table 1. Example of risk responsibility matrix.

	Team members (TM)						
Risk UIDN	TM_1	TM_2	TM_3	TM_4	Project manager	High management	Client management
6.4.3.2.5.1	O		S		A		
6.4.3.2.5.2		O		S	A	A	
6.4.3.2.5.3	S		S	O			A
6.4.3.2.5.4		S	O			A	
6.4.3.2.5.5	S	O		S	A		A

Note: O, owner; S, support; A, approve.

The fuzzy risk ownership score (ROS) is defuzzified using the centre of area method presented in eq. (3), and hence the candidate with highest score is selected as owner of the risk being considered. Then, a risk responsibility matrix (RRM) is introduced to distribute risk responsibilities among project stakeholders in cases where a risk may represent an exposure to more than one

Fig. 4. Risk assessment using fuzzy theories at task level.



member of project stakeholders. The RRM, shown in Table 1, represents a combination of the introduced MRBS and the responsibility assignment matrix (RAM). The RAM is introduced by PMI (2013) and is used currently by practitioners to assign responsibilities of an activity to members of project team. The RRM interprets the relation, whether to support (S) or to approve (A), between responsible team member and risk owner (O). Support members are responsible to support risk owner in managing the occurred risk, and approval members are responsible to approve deviations from the risk mitigation plan if deemed necessary. Table 1 illustrates an example of RRM that represents the risk owner (O), support members (S), and approval members (A) of each risk. This risk owner determination procedure addresses the inappropriate risk allocation (e.g., contractual) which assigns risk items to a project stakeholder with minimum effort and cost regardless of the capacity and ability to efficiently manage the risk.

Risk register generation

Identification of risk items, selection of risk owner, and generation of risk responsibility matrix allow users to generate a risk register that includes risk details such as: UIDN, risk owner, support members, approval members, and risk description. However, the risk register is usually extended in progressing with assessment, mitigation, monitoring, and control processes. The use of micro approach facilitates the transition between risk identification process and risk assessment process because it considers risk items at the micro level.

Proposed assessment method

Risk register items at the task level are evaluated, qualitatively and quantitatively, using fuzzy set theory (Zadeh 1965) and fuzzy probability theory (Zadeh 2008). Risk assessment team should be subdivided into subgroups, based on their experience, to evaluate risk consequences, and probability of occurrence using a linguistic or numeric fuzzy numbers. Linguistic fuzzy representation (e.g., low, medium, and high) allows experts to express their judgment intuitively in cases where it becomes difficult to express that using numeric evaluation. The proposed risk assessment method incorporates seven steps: fuzzy evaluation, fuzzy linguistic numeric conversion scheme (FLNCS), qualitative assessment, risk mapping, quantitative assessment, and contingency estimating.

Fuzzy evaluation

In this process, each expert "*j*" evaluates numerically the fuzzy consequences and fuzzy probability for each risk item "*i*" as shown in Fig. 4. The numerical fuzzy evaluations can be represented using a quadruple of real numbers ranging from 0 to 10; where 0 denotes very low and 10 denotes very high. If such numeric evaluation is impossible, experts can evaluate risk components using linguistic evaluations which could be converted at a later stage into numeric using a conversion scheme.

Table 2. Experts input for lower and upper boundaries.

Fuzzy system								
	Very low	Low		Medium		High		Very high
Experts	Lower than or equal	Between		Between		Between		Higher than or equal
E1	1	1	4	3.5	6	6	9	8.5
E2	2	2	5	3.5	7	7	9.5	9
E3	2	2	4	4	7.5	7	9	10
E4	2.5	2	5	3.5	7.5	7	9.5	10

Table 3. Uniform fuzzy numbers representation.

Fuzzy attribute	Lower bound	Upper bound	Uniform fuzzy number
Very low	0	2.5	[0,3.5]
Low	1	5	[1,5]
Medium	3.5	7.5	[3.5,7.5]
High	6	10	[6,10]
Very high	8.5	10	[8.5,10]

Fuzzy linguistic numeric conversion scheme

In this phase, fuzzy linguistic conversion scheme (FLNCS) is generated; based on organizational and (or) project requirements. The data collected from experts represent the interrelation between linguistic term (e.g., very low) and respective numeric fuzzy evaluations. Generation of the FLNCS includes the following three steps:

Step 1. Define lower and upper boundaries of each fuzzy attribute

Each fuzzy attribute (i.e., low) is represented by its lower boundary (LB) and upper boundary (UB), which are calculated using eqs. (6) and (7) respectively as follows:

$$\mathrm{LB}_i = \bigwedge_{j=1}^{j=m} \mathrm{LB}_{ij} \tag{6}$$

Fig. 5. Fuzzy linguistic numeric conversion scheme: (*a*) preliminary and (*b*) final.

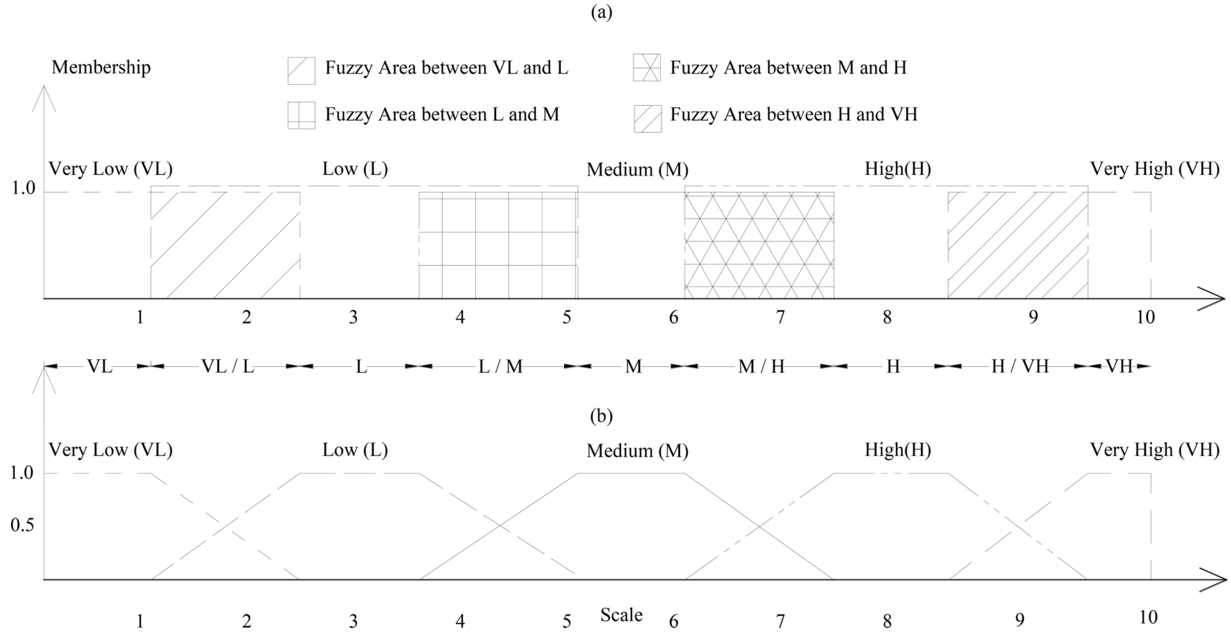
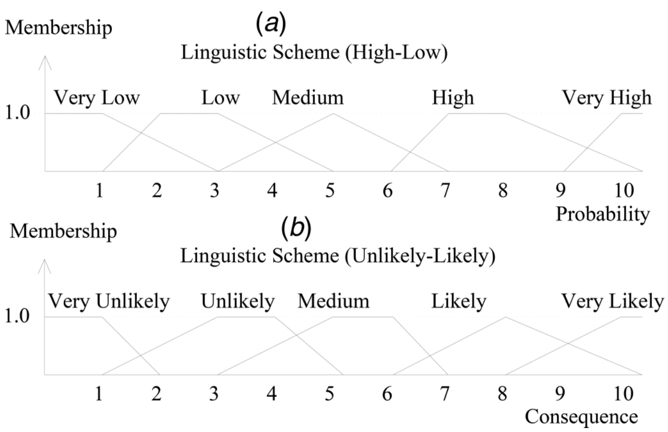


Fig. 6. Examples of FLNCS for (*a*) probability and (*b*) consequence.



$$\mathrm{UB}_i = \bigvee_{j=1}^{j=m} \mathrm{UB}_{ij} \tag{7}$$

where LB_{ij} and UB_{ij} represent, respectively, the lower and upper boundary of fuzzy attribute "*i*" evaluated by expert "*j*".

Table 2 shows an example of experts input used to generate the lower and upper bounds for each fuzzy attribute using eqs. (1) and (2) respectively.

Step 2. Generate uniform fuzzy number of each fuzzy attribute

Uniform fuzzy number which represents each fuzzy attribute is generated using the lower and upper bounds calculated in "step 1". The uniform fuzzy number (*F*) of attribute (*i*) can be expressed using eq. (8) as follows:

$$F_i = (\mathrm{LB}_i, \mathrm{UB}_i) \tag{8}$$

Using the inputs presented in Table 2, the uniform fuzzy number of each attribute can be calculated as shown in Table 3.

Step 3. Generation of FLNCS

Table 4. Risk mapping scheme and colour code.

Qualitative risk value (%)	Criticality scheme	Colour code
0–5	Very non-critical	1- Blue
5–20	Non-critical	2- Green
20–50	Medium	3- Yellow
50–80	Critical	4- Orange
80–100	Very critical	5- Red

Fig. 7. Example of risk mapping.

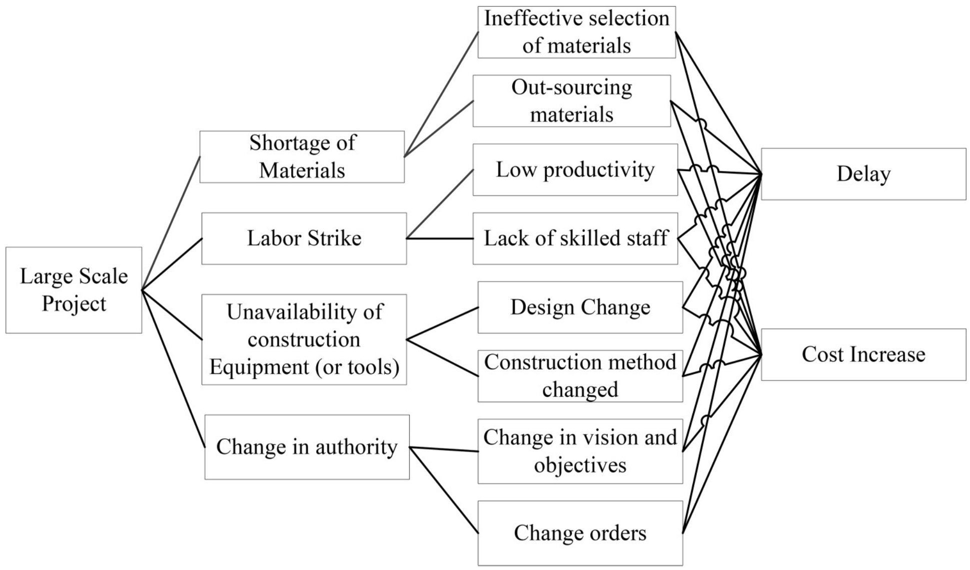
<table>
<tr><td colspan="5">Project1</td></tr>
<tr><td colspan="5">Category 2</td></tr>
<tr><td colspan="5">Package 1</td></tr>
<tr><td colspan="5">Activity 5</td></tr>
<tr><td colspan="5">Task 1</td></tr>
<tr><td>2</td><td>5</td><td>5</td><td>1</td><td>3</td></tr>
<tr><td>4</td><td>5</td><td>5</td><td>3</td><td>2</td></tr>
<tr><td>5</td><td>4</td><td>3</td><td>5</td><td>4</td></tr>
<tr><td>3</td><td>3</td><td>4</td><td>4</td><td>4</td></tr>
<tr><td>3</td><td>3</td><td>5</td><td>2</td><td>3</td></tr>
</table>

The uniform fuzzy numbers generated in "step 2" are used to generate preliminary fuzzy linguistic numeric conversion scheme using fuzzy areas, which represent the common area between two consecutives fuzzy attributes (e.g., low and medium), as shown in Fig. 5*a*.

The final FLNCS is generated by linking the boundaries of each fuzzy area using two straight lines; the first links upper-left to lower-right and belongs to left attribute. And the second links lower-left to upper-right and belongs to right attribute as shown in Fig. 5*b*.

Experts evaluate consequences and probabilities of each risk item using either numeric, or linguistic fuzzy number without

Fig. 8. Risks associated with large-scale project criterion.



any information about the selected conversion scheme (FLNCS). Two examples of FLNCS for consequence (Fig. 6*a*) and probability (Fig. 6*b*) are used to convert linguistic evaluations into numeric. For example, if an expert "*j*" evaluates the consequence and probability of occurrence of a risk "*i*" as "likely" and "high" respectively then, numeric fuzzy number for risk components can be presented as $\tilde{C}_{ij} = (6,8,10)$ and $\tilde{P}_{ij} = (6,7,8,10)$.

Qualitative assessment

The qualitative assessment uses fuzzy number calculations (Moselhi and Salah 2012; Carlsson et al. 2004) to add or multiply fuzzy numbers. Fuzzy consequence and probability of occurrence for each risk item are calculated using fuzzy arithmetic addition (Zadeh 1965) as shown in eqs. (9) and (11) respectively. Fuzzy membership functions consequence and probability of occurrence of each risk are generated using eqs. (10) and (12) respectively. The fuzzy risk value (*R*) for each risk item is calculated using fuzzy arithmetic multiplication (Zadeh 1965) as shown in eq. (13). The membership function of each risk value is generated using eq. (15).

$$(9) \qquad \tilde{C}_i = \left[\bigwedge_{j=1}^{j=m} c_{ij1}, \bigwedge_{j=1}^{j=m} c_{ij2}, \bigvee_{j=1}^{j=m} c_{ij3}, \bigvee_{j=1}^{j=m} c_{ij4}\right]$$

$$(10) \qquad \mu_{\tilde{C}_i}(x) = \begin{cases} 1 - \prod_{j=1}^{m} [1 - \mu_{\tilde{C}_{ij}}(x)], C_{i1} < x < C_{i2} \\ 1, C_{i2} < x < C_{i3} \\ 1 - \prod_{j=1}^{m} [1 - \mu_{\tilde{C}_{ij}}(x)], C_{i3} < x < C_{i4} \\ 0, \text{Otherwise} \end{cases}$$

Similarly, the risk's probability could be represented as follows:

$$(11) \qquad \tilde{P}_i = \left[\bigwedge_{j=1}^{j=m} \mathrm{p}_{ij1}, \bigwedge_{j=1}^{j=m} \mathrm{p}_{ij2}, \bigvee_{j=1}^{j=m} \mathrm{p}_{ij3}, \bigvee_{j=1}^{j=m} \mathrm{p}_{ij4}\right]$$

$$(12) \qquad \mu_{\tilde{P}_i}(y) = \begin{cases} 1 - \prod_{j=1}^{m} [1 - \mu_{\tilde{P}_{ij}}(y)], P_{i1} < y < P_{i2} \\ 1, P_{i2} < y < P_{i3} \\ 1 - \prod_{j=1}^{m} [1 - \mu_{\tilde{P}_{ij}}(y)], P_{i3} < y < P_{i4} \\ 0, \text{Otherwise} \end{cases}$$

The risk value can be calculated using the fuzzy multiplication operation as follows:

$$(13) \qquad \tilde{R}_i = \frac{1}{\alpha}(C_{i1} \times P_{i1}, C_{i2} \times P_{i2}, C_{i3} \times P_{i3}, C_{i4} \times P_{i4})$$

where α represents the scale factor that transforms the risk value to a value from 0 to 1. The scale factor (α) is calculated using eq. (14) as follows:

$$(14) \qquad \alpha = \text{scale}(C) \times \text{scale}(P)$$

where scale (*P*) and scale (*C*) represent the scales used to evaluate the fuzzy probability and fuzzy consequence, respectively (e.g., scale 0–10; 1–5).

The membership function of risk value is calculated using eq. (2) and it is presented as shown in eq. (15).

$$(15) \qquad \mu_{\tilde{R}_i}(z = x \times y) = \begin{cases} \mu_{\tilde{C}_i}(x) \times \mu_{\tilde{P}_i}(y), \quad C_{i1} < x < C_{i2} \text{ and } P_{i1} < y < P_{i2} \\ 1, \quad C_{i2} < x < C_{i3} \text{ and } P_{i2} < y < P_{i3} \\ \mu_{\tilde{C}_i}(x) \times \mu_{\tilde{P}_i}(y), \quad C_{i3} < x < C_{i4} \text{ and } P_{i3} < y < P_{i4} \\ 0, \text{Otherwise} \end{cases}$$

The fuzzy risk values calculated, using eq. (13), are defuzzified using eq. (3).

Risk mapping

The developed risk mapping utilizes the qualitative risk value "R_i" that ranges from 0 to 1. It illustrates graphically the criticality of each project component from risk level up to project level. The introduced risk mapping scheme (Table 4) and the micro approach presented in Fig. 2, jointly allow for the generation of risk mapping for the project being considered. Figure 7 presents an example of risk mapping for "Task #3" where each square represents one risk item and the colour code indicates the criticality of this risk. Similarly, mapping of the risk level associated with each project components (i.e., activity, package, and category) can be generated. The developed risk mapping provides graphical representation of the criticality of each project component without delving into details. It should be noted that, the mapping scheme

Fig. 9. Risk items associated with enthusiastic owner criterion.

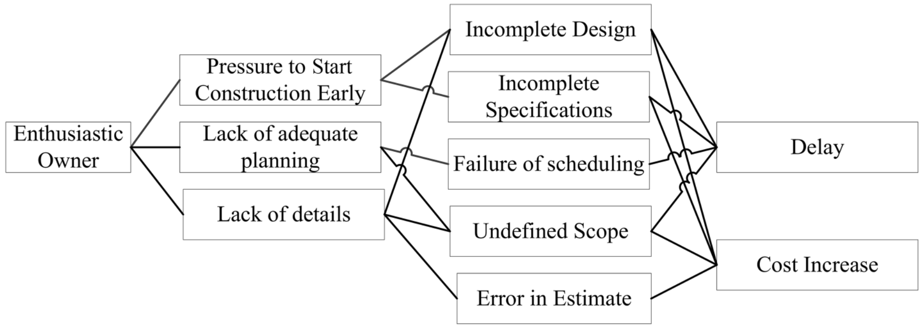
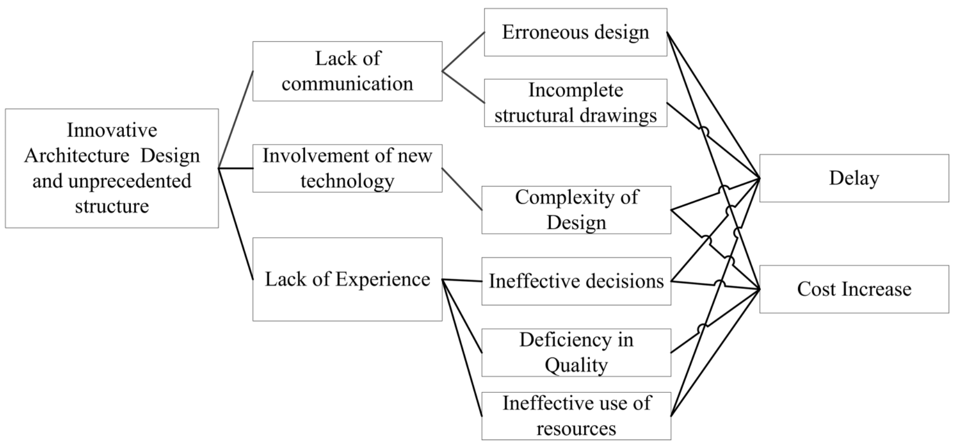


Fig. 10. Risks associated with innovative architecture and unprecedented structure.



is an organization dependent, and therefore each organization sets a scheme of criticality similar to that shown in Table 4.

Quantitative assessment

The qualitative risk values alone are meaningless in expressing monetary impact; therefore it is important to evaluate the risk quantitatively. The proposed quantitative assessment method calculates the quantitative risk value or pre-mitigation contingency (PREMC_i) using its respective qualitative risk value "R_i" and expected monetary value (EMV_i). The PREMC represents the contingency fund allocated to mitigate a risk regardless of the mitigation strategy being employed. The expected monetary value (EMV_i) of each risk item is calculated using an explicit list of risk consequences identified by experts. Each risk item "i" has "n" consequences evaluated by "m" experts using fuzzy set theory. The fuzzy expected monetary value of consequence (k) associated with risk (i) evaluated by expert (j) is presented as $\widetilde{\mathrm{EMV}}_{ijk}$.

Using fuzzy arithmetic addition and fuzzy arithmetic combination, $\widetilde{\mathrm{EMV}}_{ij}$ and $\widetilde{\mathrm{EMV}}_i$ are calculated using eqs. (16) and (17), respectively.

$$(16)\qquad \widetilde{\mathrm{EMV}}_{ij} = \sum_{k=1}^{n} \widetilde{\mathrm{EMV}}_{ijk} = \left(\sum_{k=1}^{k=n} \widetilde{\mathrm{EMV}}_{ijk1}, \sum_{k=1}^{k=n} \widetilde{\mathrm{EMV}}_{ijk2}, \sum_{k=1}^{k=n} \widetilde{\mathrm{EMV}}_{ijk3}, \sum_{k=1}^{k=n} \widetilde{\mathrm{EMV}}_{ijk4} \right)$$

$$(17)\qquad \widetilde{\mathrm{EMV}}_{i} = \left[\bigwedge_{j=1}^{j=m} \widetilde{\mathrm{EMV}}_{ij1}, \bigwedge_{j=1}^{j=m} \widetilde{\mathrm{EMV}}_{ij2}, \bigvee_{j=1}^{j=m} \widetilde{\mathrm{EMV}}_{ij3}, \bigvee_{j=1}^{j=m} \widetilde{\mathrm{EMV}}_{ij4} \right]$$

Equations (16) and (17) are used to represent the fuzzy numbers which represent the addition of independent fuzzy numbers (i.e., A and B) and dependent fuzzy numbers (e.g., A_i). The independent fuzzy numbers are added using the fuzzy arithmetic addition, for example, if $A = [a_1, a_2, a_3, a_4]$ and $B = [b_1, b_2, b_3, b_4]$ then, $A + B = [a_1 + b_1, a_2 + b_2, a_3 + b_3, a_4 + b_4]$. In the other hand, the dependent

Fig. 11. FLNCS for probability and consequence of SOH case study.

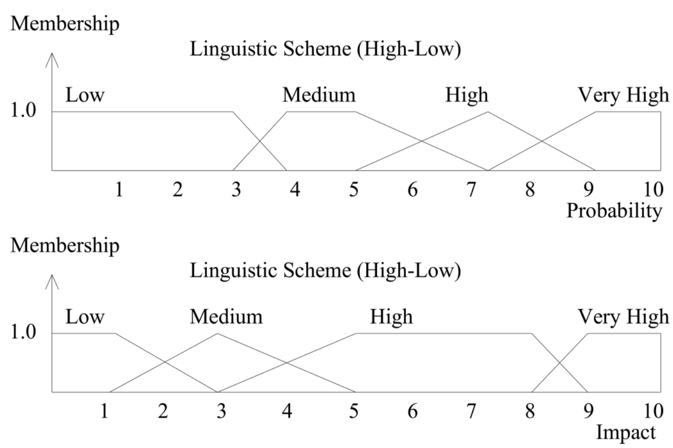


Table 5. Colour mapping scale.

Mapping scale	Criticality scheme / Mapping colour
R<0.2	L - Low / 1 - Green
0.2<R<0.30	M - Medium / 2 -Yellow
0.30<R<0.50	H - High / 3 - Red
R>0.50	C - Critical / 4 - Brown

Table 6. SOH qualitative risk assessment using the developed method

Risk	P	I	FLNCS(P)	FLNCS(C)	Fuzzy risk value
Poor cost estimate	H	H	(5,7,7,9)	(3,5,8,9)	(0.15,0.35,0.56,0.81)
Incomplete design	L	VH	(0,0,3,4)	(8,9,10,10)	(0,0,0.3,0.4)
Changes in project scope and requirement	L	H	(0,0,3,4)	(3,5,8,9)	(0,0,0.24,0.36)
Design change	M	M	(3,4,5,7)	(1,3,3,5)	(0.03,0.12,0.15,0.35)
Inaccurate contract time estimate	H	VH	(5,7,7,9)	(8,9,10,10)	(0.4,0.63,0.7,0.9)
Inadequately defined roles and responsibilities	M	VH	(3,4,5,7)	(8,9,10,10)l	(0.24,0.36,0.5,0.7)
Insufficient skilled staff	L	M	(0,0,3,4)	(1,3,3,5)	(0,0,0.09,0.2)
Political risks	VH	M	(7,9,10,10)	(1,3,3,5)	(0.07,0.27,0.3,0.5)

Table 7. Comparison of qualitative risk assessment results.

Risk	Fuzzy risk value	Defuzzified value	Developed method	Burtonshaw-Gunn (2013)
1. Poor cost estimate	(0.15,0.35,0.56,0.81)	0.518	C	C
2. Incomplete design	(0,0,0.3,0.4)	0.302	H	H
3. Changes in project scope and requirement	(0,0,0.24,0.36)	0.259	M	H
4. Design change	(0.03,0.12,0.15,0.35)	0.191	L	L
5. Inaccurate contract time estimate	(0.4,0.63,0.7,0.9)	0.67	C	C
6. Inadequately defined roles and responsibilities.	(0.24,0.36,0.5,0.7)	0.473	H	H
7. Insufficient skilled Staff	(0,0,0.09,0.2)	0.126	L	L
8. Political risks	(0.07,0.27,0.3,0.5)	0.320	H	M

numbers, which represent the evaluations of experts for same fuzzy variable "A", are combined using the fuzzy arithmetic combination. For example, if $A_1 = [a_{11}, a_{21}, a_{31}, a_{41}]$ and $A_2 = [a_{12}, a_{22}, a_{32}, a_{42}]$ represent, respectively, the evaluations of experts 1 and 2 for the fuzzy number "A", then, the fuzzy number "A" can be represented as $A = [\min[a_{11}, a_{12}], \min[a_{21}, a_{22}], \max[a_{31}, a_{32}], \max[a_{41}, a_{42}]]$.

Using fuzzy membership function addition (eq. (2)), membership functions of $\widetilde{\mathrm{EMV}}_{ij}$, and $\widetilde{\mathrm{EMV}}_i$ are generated using eqs. (18) and (19) respectively as follows:

$$(18)\qquad \mu_{\widetilde{\mathrm{EMV}}_{ij}} = \frac{1}{n}\sum_{k=1}^{n} \mu_{\widetilde{\mathrm{EMV}}_{ijk}}$$

$$(19)\qquad \mu_{\widetilde{\mathrm{EMV}}_i}(y) = \begin{cases} 1 - \prod_{j=1}^{m}[1 - \mu_{\widetilde{\mathrm{EMV}}_{ij}}(y)], & \mathrm{EMV}_{i1} < y < \mathrm{EMV}_{i2} \\ 1, & \mathrm{EMV}_{i2} < y < \mathrm{EMV}_{i3} \\ 1 - \prod_{j=1}^{m}[1 - \mu_{\widetilde{\mathrm{EMV}}_{ij}}(y)], & \mathrm{EMV}_{i3} < y < \mathrm{EMV}_{i4} \\ 0, & \text{Otherwise} \end{cases}$$

Then, the defuzzified value of expected monetary value of risk item "i" is calculated using eq. (3).

Fuzzy pre-mitigation contingency $\widetilde{\mathrm{PREMC}}$ of each risk item "i" and its respective membership function are calculated using eqs. (20) and (21) respectively.

$$(20)\qquad \widetilde{\mathrm{PREMC}}_i = \tilde{\mathrm{R}}_i \times \widetilde{\mathrm{EMV}}_i$$

$$(21)\qquad \mu_{\widetilde{\mathrm{PREMC}}_i}(x = z \times y) = \begin{cases} \mu_{\tilde{R}_i}(z) \times \mu_{\widetilde{\mathrm{EMV}}_i}(y), & \forall\, R_{i1} < z < R_{i2}, \text{ and } \forall\, \mathrm{EMV}_{i1} < y < \mathrm{EMV}_{i2} \\ 1, & \forall\, R_{i2} < z < R_{i3}, \text{ and } \forall\, \mathrm{EMV}_{i2} < y < \mathrm{EMV}_{i3} \\ \mu_{\tilde{R}_i}(z) \times \mu_{\widetilde{\mathrm{EMV}}_i}(y), & \forall\, R_{i3} < z < R_{i4}, \text{ and } \forall\, \mathrm{EMV}_{i3} < y < \mathrm{EMV}_{i4} \\ 0, & \text{Otherwise} \end{cases}$$

Defuzzified value of pre-mitigation contingency of risk item "i" is calculated using eq. (3) as follows:

$$(22)\qquad \mathrm{PREMC}_i = \frac{\int_{-\infty}^{+\infty} x\mu_{\widetilde{\mathrm{PREMC}}_i}(x)\mathrm{d}x}{\int_{-\infty}^{+\infty} \mu_{\widetilde{\mathrm{PREMC}}_i}(x)\mathrm{d}x}$$

Total project contingency (TC), calculated using eq. (23), represents the cumulative pre-mitigation contingencies of all risk items associated with the construction project being considered.

$$(23)\qquad \mathrm{TC}_p = \sum_{m=1}^{n_{\mathrm{cat}}}\sum_{l=1}^{n_{\mathrm{pack}}}\sum_{k=1}^{n_{\mathrm{act}}}\sum_{j=1}^{n_{\mathrm{task}}}\sum_{i=1}^{n_{\mathrm{risk}}} \mathrm{PREMC}_i$$

where n_{risk}, n_{task}, n_{act}, n_{pack}, and n_{cat} are respectively numbers of risks, tasks, activities, packages, and categories associated with project "p".

The cumulative pre-mitigation contingency highlights the total amount of risk associated with the EPCM project being considered. It also provides decision support to project owners at the early stages of project development, especially when go/no-go decision is required.

Case studies

Several case studies have been utilized to demonstrate the use of the proposed methods. These case studies include: Sydney opera house "SOH" (Burtonshaw-Gunn, 2013), urban highway construction project for quantitative assessment (Paek et al. 1993), and a numerical example that presents the allocation of risk based on newly developed procedure that allows the determination of risk ownership.

Table 8. Comparison between the traditional method and the developed identification method.

Traditional method (Burtonshaw-Gunn 2013)	Developed method	Actual situation (NSW 2003; Utzon 2002)
Poor cost estimate	Error in estimate	Initial estimate A$ 7 M
Incomplete design	Incomplete design	The roof shells were designed as a series of parabolas which was impossible to construct. Utzon changed the shells to all being created as ribs from a sphere of the same radius (75 m)
Failure to keep within the cost estimate	(Consequence)	
Failure to achieve the required completion date	(Consequence)	
Changes in project scope and requirement	Undefined scope	Ted Farmer completed the glass walls and interiors including adding three previously unplanned venues underneath the concert hall on the western side
Design change	Design change	The major hall was changed from dual purpose for concert and opera to a single purpose concert hall
Pressure to deliver the project on accelerated schedule	(Root cause)	
Inaccurate contract time estimate	Failure of scheduling	10 year delay
Lack of communication between project participants	(Root cause)	
Inadequately defined roles and responsibilities	Ineffective decisions	Minister in charge, simply refused to pay Utzon. As a result Utzon resigned in February 1966
Insufficient skilled staff	Lack of skilled staff	During the project a part-time executive, who did not have the technical competences and skills was appointed to supervise the project
Political risks	Change in vision and objectives	The new government considers the SOH as cost blow-out. So, it was tempted to call a halt to control the expenditures
	Incomplete specifications	The Sydney Opera House project had no design and cost specifications set by the client
	Ineffective selection of materials	It is a relatively dark space, due to the materials used and primarily due to the contrasting harsh sunlight at the eastern and western sides
	Out-sourcing materials	1 056 000 glazed white granite tiles imported from Sweden
	Low productivity	Payments were being delivered and no considerable progress was seen, thus the government began withholding payments to Utzon which slowed down the productivity
	Construction method change	Construction of the shells was one of the most difficult engineering tasks ever to be attempted
	Generation of change orders	The government eventually became an obstacle to the project team by inhibiting changes during the progress of the operations and thus contributed to cost overrun and delays
	Erroneous design	Utzon was pushed to start the construction before the design was even close to finalization which led to erroneous design
	Incomplete structural drawings	Construction beginning before proper engineering drawings had been prepared
	Deficiency in quality	N/A
	Ineffective use of resources	When Utzon resigns, the government appointed new architects who blew the budget from $18.4 to $102 million
	Complexity of design	Computers were needed to calculate stress points within the roof of the Sydney Opera House

Case study 1: SOH

The SOH case study was collected from literature and used to validate the proposed methods for identification and qualitative assessment. Characteristics and details of SOH are as follows:

Owner: State Government of New South Wales
Architect: Jørn Utzon
Cost: initial estimate was A$ 7 million and actual cost is A$102 million
Area: 1.8 hectares
Overrun: 1300%
Delay: 10 years

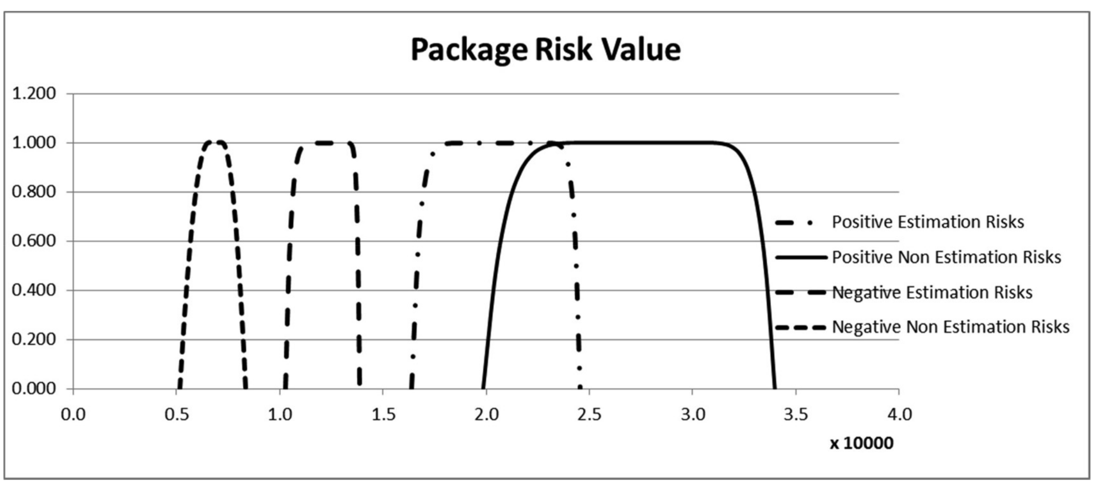
In the early stages of the SOH project vital factors were neglected such as: (1) the innovative nature of the project, (2) innovative architecture and unprecedented structure, and (3) enthusiasm of the Australian government. Considering each of these factors, the developed identification methods identify 10 root causes which lead to the identification of 19 risks associated with the project as shown in Fig. 8, Fig. 9, and Fig. 10 respectively. In comparison to the real situation, which has identified 18 risks, the relative error in identification of the traditional method, which identified only 12 risks, is 67% and that of the developed method, which identified 19 risks, is 94%. This indicates that the use of the developed method improves the identification rate by 27% as compared to the traditional method (Burtonshaw-Gunn 2013). Thus, the increased identification rate consequently is expected to consequently decrease the unexpected chances that may cripple a project or business as highlighted by Loosemore et al. (2006).

However, it should be noted that the application of the developed identification method at early stage with considerations of all project circumstances and along with the cooperation of all project parties, may help to identify more risks and subsequently avoid more problems. Also, it should be noted that the SOH case study demonstrates the use of the developed identification

Table 9. UHCOC quantitative risk assessment.

Project	Type	Group	Risks	*a*	*b*	*c*	*d*
UHCOC risks	Positive risks	Estimation risk	Top soil quantity overrun	255	285	315	345
			Additional retaining walls and pilings under retaining walls	3500	4500	5250	5500
			Additional wick-drain pipe	120	142	150	150
			Additional remedial excavation in lieu of wick-drain pipe	1400	1800	2000	2400
			Rock quantity overrun - drill and shoot by 25%	2550	3230	3570	4250
			Additional 1 mile hauling distance of drill and shoot rock	2000	2375	2625	3000
			Disposal fee $1.0/cu. yd. for drill and shoot rock	4165	4752	5047	5625
			Increase in all storm drainage pipe by 6 in.	1040	1170	1430	1560
			Increase in reinforced concrete pipe by 15%	1360	1615	1700	1700
			Fuzzy risk value for positive estimation risks	16390	19869	22087	24530
		Non estimation risks	Schedule acceleration	5250	6750	7500	8625
			DBE by 20%	800	900	1000	1150
			Design growth	3000	5100	6600	7500
			Design and approval delays	2800	3600	4400	5200
			Regulatory agencies	3750	4750	5250	6000
			Disposal of excess materials	4250	4750	5000	5500
			Fuzzy risk value for positive non-estimation risks	19850	25850	29750	33975
		Fuzzy risk value for positive risks		36240	45719	51837	58505
	Negative risks	Estimation risk	Less remedial excavation in lieu of wick-drain pipe	285	297	300	300
			less retaining walls and pilings under retaining walls	3200	3800	4200	4600
			Fatten slopes on site waste from drill and shoot rock	2400	2700	3000	3000
			Less tire/track/repair cost	935	1067	1133	1265
			Less equipment maintenance cost	996	1140	1260	1404
			Piling reduction by 6 ft per pile under bridge	720	873	900	900
			Replace 78 R-value rock with 50 R-value rock	1725	2185	2300	2415
			Fuzzy risk value for negative estimation risks	10261	12062	13093	13884
		Non estimation risks	Schedule deceleration	3750	4750	5000	5750
			Less design and approval delays	1400	1800	2200	2600
			Fuzzy risk value for negative non-estimation risks	5150	6550	7200	8350
		Fuzzy risk value for negative risks		15411	18612	20293	22234
	Total UHCOC project risks			20829	27107	31544	36271
Defuzzified value of UHCOC project				28850100			

Fig. 12. Risk values for positive/negative estimation and non-estimation risks Associated with UHCOC project.



method. However, it does not test the capabilities of the developed method in various stages of project execution.

The SOH case study was also used to demonstrate the use of qualitative assessment method. The risks associated with the SOH project were assessed by Burtonshaw-Gunn (2013) using a scale from 1 to 4 for impact and probability of occurrence where 1, 2, 3, and 4 denote respectively low, medium, high, and critical.

The linguistic terms were converted into numeric using the FLNCS presented in Fig. 11. The colour mapping scale and criticality scheme used in the developed method are shown in Table 5. The results of linguistic-numeric conversion for probability of occurrence and impact are presented in Table 6. The fuzzy risk value and its membership function, shown in Table 6, of each risk item are calculated using eqs. (13) and (15) respectively. The centre

Fig. 13. Risk values of positive and negative risks associated with UHCOC project.

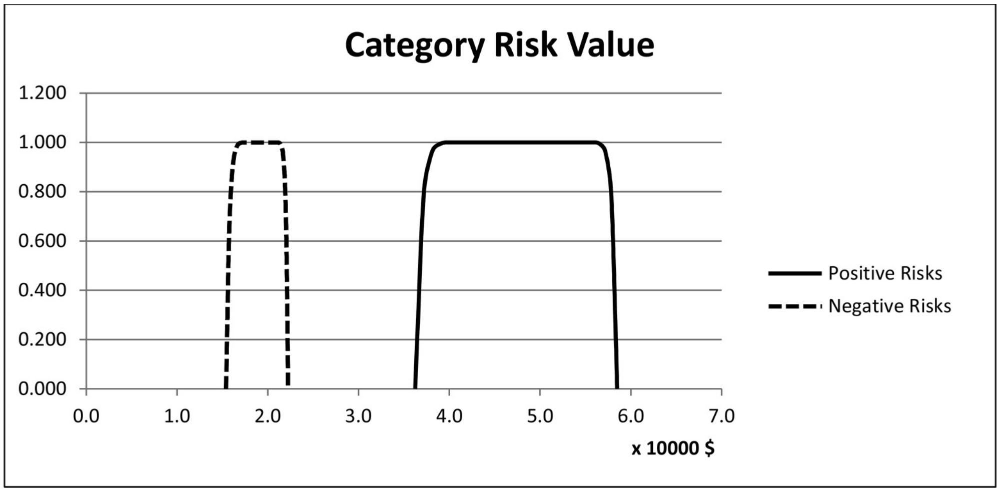
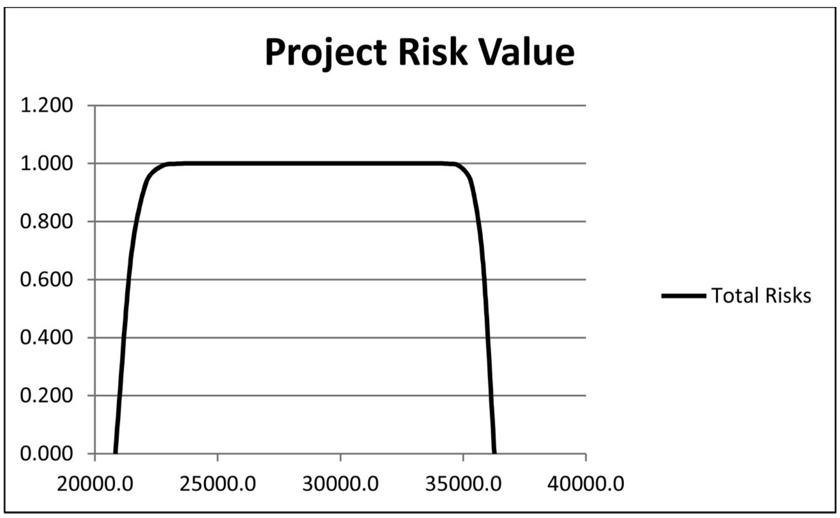


Fig. 14. Risk value of UHCOC project.



of area (COA) defuzzification method presented in eq. (3) was used to calculate the defuzzified risk value as presented in Table 7. The results of qualitative assessment of SOH risks using the developed method are compared to those reported by Burtonshaw-Gunn (2013) as shown in Table 8. This comparison shows differences in assessment of "changes in project scope and requirement" (M-H) and "political risks" (H-M). These differences are attributed to the limit that separates the medium criticality area from the high criticality area in the mapping scheme, shown in Table 5, used by the developed method and the risk matrix used by Burtonshaw-Gunn (2013). Besides these differences, the SOH case study demonstrates the applicability of the developed method for qualitative risk assessment and illustrates its features. However, it should be noted that the developed method uses fuzzy theory that assists project managers to model the uncertainty associated with input data utilized in the qualitative assessment process. Also it generates a graphical representation of risks, which is expected to assist project managers in identifying the critical risks associated with the project.

Case study 2: UHCOC

This case study, referred to as UHCOC project, was collected from literature (Paek et al. 1993) and used to validate the developed quantitative risk assessment. It represents a real PPP project for urban highway construction that consists of 32.18 km of highway with 80 various types of bridge structures. The cost of the project was projected to be approximately $800 million, and it was scheduled to be completed within 1500 calendar days including the design phase. Qualitative information does not exist or it was not provided by Paek et al. (1993), therefore, calculation of pre-mitigation contingency assumed that the qualitative risk value of each risk element equals to 1. Table 9 presents the quadruples [a, b, c, d] which represent the fuzzy evaluations of non-estimation and estimation-related negative and positive risks. Since all risk items are independent, then, fuzzy arithmetic addition (i.e., $A + B = [a_1 + b_1, a_2 + b_2, a_3 + b_3, a_4 + b_4]$) is used to calculate the fuzzy risk value associated with each component (e.g., positive estimation-related risks) of UHCOC project. However, it should be noted that in the case where each risk item receives j evaluations from experts then, the fuzzy arithmetic combination (i.e., $A = [a_1 = \min[a_{11}...a_{1j}], a_2 = \min[a_{21}...a_{2j}], a_3 = \max[a_{31}...a_{3j}], a_4 = \max[a_{41}...a_{4j}]]$) is used to calculate the fuzzy number that represents each risk item prior to the application of fuzzy arithmetic addition. The membership function of the different UHCOC project components

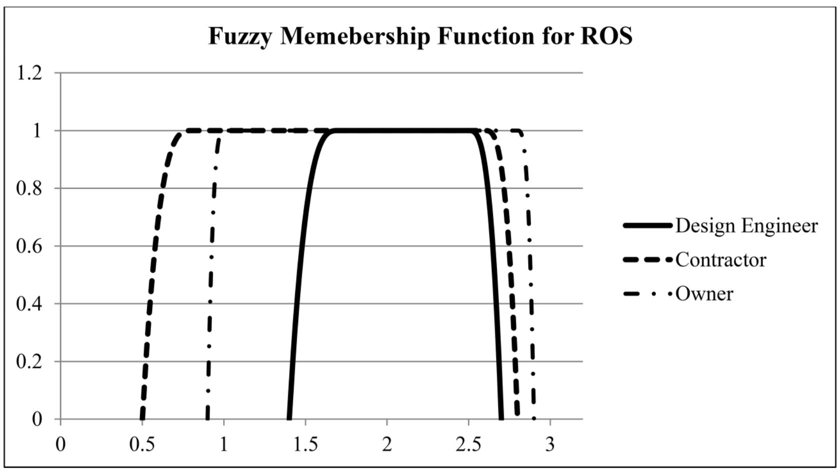
Table 10. Comparison of UHCOC results among different methods.

Project	Developed method ($)	Salah (2012)	Moselhi (1997) using PERT ($)	Paek et al. (1993) ($)
UHCOC	28 850 100	28 872 500	29 292 000	28 968 350.00

Table 11. Ranking of owners using risk ownership score (ROS).

Risk owner	Experts	Fuzzy indices of each criteria												Fuzzy ROS				ROS	Rank
		Capacity				Effectiveness				Ability									
Design engineer	1	0.4	0.5	0.6	0.8	0.4	0.5	0.6	0.7	0.8	0.9	0.9	1.0	1.40	1.70	2.50	2.70	2.05	1
	2	0.4	0.5	0.6	0.6	0.3	0.4	0.5	0.7	0.7	0.8	0.9	1.0						
	3	0.6	0.7	0.8	0.9	0.5	0.6	0.7	0.8	0.8	0.9	1.0	1.0						
	$\sum$	0.4	0.5	0.8	0.9	0.3	0.4	0.7	0.8	0.7	0.8	1.0	1.0						
Contractor	1	0.3	0.4	0.5	0.6	0.5	0.7	0.7	0.8	0.5	0.6	0.7	0.8	0.50	0.80	2.60	2.80	1.65	3
	2	0.1	0.2	0.4	0.5	0.6	0.8	0.8	0.9	0.1	0.2	0.3	0.4						
	3	0.2	0.3	0.3	0.5	0.7	0.7	0.8	0.8	0.3	0.3	0.5	0.5						
	$\sum$	0.1	0.2	0.8	0.9	0.3	0.4	0.8	0.9	0.1	0.2	1.0	1.0						
Owner	1	0.1	0.2	0.3	0.4	0.7	0.8	0.9	1.0	0.3	0.4	0.4	0.5	0.90	1.00	2.80	2.90	1.9	2
	2	0.2	0.2	0.5	0.5	0.8	0.8	0.9	0.9	0.2	0.2	0.4	0.4						
	3	0.1	0.1	0.3	0.4	0.7	0.7	1.0	1.0	0.2	0.3	0.4	0.6						
	$\sum$	0.1	0.1	0.8	0.9	0.7	0.7	1.0	1.0	0.1	0.2	1.0	1.0						

Fig. 15. Fuzzy membership function of ROS for each risk owner.



are presented in Fig. 12, Fig. 13, and Fig. 14 respectively. Equation (3) is used to defuzzify the membership function of UHCOC project, presented in Fig. 14. The defuzzified value of UHCOC project, which is equal to $28 850 100 as shown in Table 9, represents the pre-mitigation contingency required for managing all risk elements associated with UHCOC. Table 10 shows a comparison between the results of developed method and that of Paek et al. (1993), Salah (2012), and Moselhi (1997). The results are similar to those generated by the fuzzy set based methods developed by Paek et al. (1993), and Salah (2012), and the PERT used by Moselhi (1997). However, the developed method overcomes the complicated procedure of the method developed by Paek et al. (1993) and the restrictive trapezoidal shape of the membership functions as in the method developed by Salah (2012). Also, the developed method introduces the pre-mitigation contingency that represents an early warning that assists owners to make go/no-go decisions. It also assists project managers to control the budget by making use of the highlighted most costly risk items.

Case example: risk ownership determination

A case example is analyzed to demonstrate the use of the proposed methods for risk identification and assessment. Risk planning team identifies a steel reinforcement design error associated with the design of concrete columns (CCRDE) using the developed identification method. However, the risk needs to be allocated to a risk owner among three candidates from the project stakeholders: contractor, engineer, and owner. Thus, the developed allocation method is employed to determine the risk owner who has the ability, capacity, and effectiveness to better manage CCRDE risk. Three experts evaluated the ability, capacity, and effectiveness of each candidate as shown in Table 11. The risk ownership score and its defuzzified value are calculated, respectively, using eq. (4) and eq. (3) as shown in Table 11. The membership functions, generated using eq. (5), for each ownership candidate, are presented in Fig. 15. The defuzzified values of the risk ownership score of each candidate are presented in Table 11. Thus, CCRDE is allocated to the design engineer and his team as shown in Table 11. However, the project manager and engineering manager have the approval authorities for any deviation from the CCRDE risk response plan. This procedure is followed for each newly identified risk to generate a risk allocation database that is used, in future projects, for automating the allocation procedure. The developed risk owner selection procedure provides a systematic allocation method that substitutes the inappropriate and unreasonable contractual risk assignment as highlighted by Hanna et al. (2013) and Peckiene et al. (2013).

Summary and concluding remarks

Two newly developed methods for risk identification and assessment are presented. The developed identification method introduces micro level risk breakdown structure and risk responsibility matrix. It also introduces newly developed procedure for risk ownership determination which allows the selection of the most suitable risk owner based on a set of criteria. The developed assessment method introduces a new method for qualitative and quantitative assessment of risk items associated with EPCM projects using fuzzy set theory. The generic feature of the developed methods allows its application to other types of projects. Integration of the root-cause analysis, cause effect diagram, and brainstorming methods in a comprehensive framework assists users to identify known and majority of unknown risk items. Selection of risk owner considers the effectiveness, ability, and capacity of that owner to better manage the risk being considered; however, other criteria may be identified and integrated within the developed procedure. The developed risk mapping procedure highlights and presents graphically the criticality of each project risk item without delving into details. The introduced premitigation contingency provides an early warning decision support tool that assists owners to take go/no-go decisions. The results of selected case studies and the case example show the applicability of the developed methods and highlight their features. However, application of developed methods on the same case study may assist in evaluating the interactions among the identification, allocation, and assessment processes. Finally, it should be noted that the first application of developed methods can be time consuming especially in the data collection stage, however, these data can subsequently be utilized for risk identification and assessment of future projects.

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List of symbols

C	consequence
P	probability of occurrence
R	risk value
PREMC	pre-mitigation contingency
EMV	expected monetary value
TC	total contingency
CCRDE	concrete columns reinforcement design error
LB	lower bound
UB	upper bound
F	uniform fuzzy number
μ	membership function
ROS	risk ownership score
Ab, AbI	ability, ability index
Ef, EfI	efficiency, efficiency index
Ca, CaI	capacity, capacity index
TM	team member
UIDN	unique identification number
α	scale factor
RRM	rsk responsibility matrix