Project risk management using fuzzy failure mode and effect analysis and fuzzy logic

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Abstract: Risk management is one of the most important phases of the project management which attracts increasing attentions of many researchers. The proposed method in this research considers different kinds of risk through the project life cycle. We combine fuzzy failure mode and effect (FMEA) and some weighting methods for determination of project risk magnitude. Our method uses five factors; severity, occurrence, not detection, project phase's weight and risk weight for evaluation of risks and also selecting an appropriate risk response. In fact, our model covers four parts of risk management process: risk management planning, risk identification, quantitative risk analysis and risk response planning. Finally, we use this model for a given construction company to show how it can be employed in reality.

Keywords: fuzzy analytic hierarchy process; FAHP; project risk management; fuzzy rules; failure mode and effect; FMEA.

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1 Introduction

According to the project management body of knowledge (PMI, 2004) definition "a project is a temporary endeavour under taken to create a unique product, service and result. Project management is the application of knowledge, skills, tools and techniques to project activities to meet project requirements in the project life cycle that includes the phases that connect the beginning of the project to its end. Project management is accomplished through the application and integration of the process of initiating, planning, executing, monitoring and controlling and closing". The most important project constraints are 'scope', 'time' and 'cost' (project management triangular). Risk is an inherent factor in managing of these three factors and project risk management is a tool for considering positive and negative effects of any change in the mentioned constraints.

So, risk management is an essential process in project management and should be included in all stages of the project life cycle.

Project risk management is "an endeavour to increase the probability and impact of positive events and decreases the probability and impact of events adverse to the project that concerned with conducting risk management planning, risk identification, qualitative risk analysis, quantitative risk analysis, risk response planning and risk monitoring and control on a project'. Risk management is an essential part of project management and plays such an important role that its application goes beyond the traditional scope which normally centres on the construction phase. For example, it expands to such fields as bid-decision making, feasibility studies, marketability studies, performance evaluations and contingency management by reflecting the various factors spanning all phases of the project life cycle. In fact, it can help managers to optimise the outcome, being proactive in evaluating risk and the possible responses using this information to best effect, demonstrating the need for changes in project plans, taking the necessary actions and monitoring the effects (Caño and Cruz, 2002; Chapman and Ward, 1997; Han et al., 2008). Formal risk management process (RMP) should be applied at all stages in the project life cycle and should consider several potential aspects such as technology, market, financial, operational, organisational and business. This guaranties the selection of the most appropriate risk treatment strategy (Aelion et al., 1995; Aloini et al., 2007). Risks may arise at different phases of a project life cycle and some of them are possibly concerned with more than one phase. Many researchers have studied risk management in a particular project phase. For instance, Uher and Toakley (1999) investigated various structural and cultural factors concerned with the implementation of risk management in the conceptual project phase (i.e., feasibility stage). Abdou (1996) classified construction risks into three groups; construction finance, construction time and construction design and addressed these risks in detail in light of the different contractual relationships existing among the functional entities involved in the design, development and construction of a project. Sharratt and Choong (2002) proposed a methodology to recognise and assess risks in a project that arise from environmental issues. They used life-cycle framework to identify the mass and energy flows associated with the activities throughout the project and their relevant environmental problems. Xie et al. (2006) explored how to integrate software project management risk into bidding risk and made use of life cycle management theory to study risk avoidance in bidding for software projects. A project specific risk management concept entitled 'ConSERV' was developed by Conroy and Soltan (1998) as a comprehensive project management methodology able to extract project specific risk issues throughout the project life cycle and apply experiential knowledge by using a knowledge-based system to assist in the risk management. In this way, the user can visualise the overall 'shape' of the project risks at a particular time over the project life cycle more easily. Despite the importance of response phase in reducing the likelihood of the risk occurrence and/or the magnitude of their negative impact, it has not attracted enough attention in literature. Some of the existing researches in risk response area are DSMC (1986) who reviewed examples of risk handling in weapon development projects, Tsai (1992) who interviewed management in weapon development projects and proposed seven risk-handling strategies.

Jegadheesan et al. (2007) designed and developed a service failure mode and effects (FMEAs) analysis model. This direction of research led to the design of an improved model, named as 'modified service FMEA'. Its implementation was examined in an Indian State Government owned passenger transport company. Despite certain practical hurdles, this exercise was successful in developing modified service FMEA table and pinpointing the seriousness of failures through the portrayal of service lost (SL) and cost lost (CL). Mesut and PıNar (2013) applied a fuzzy-based FMEA to improve the purchasing process of a public hospital. Results indicate that the application of fuzzy FMEA method can solve the problems that have arisen from conventional FMEA and can efficiently discover the potential failure modes and effects. It can also provide the stability of process assurance. Barends et al. (2012) proposed a probabilistic modification of FMEA, replacing the categorical scoring of occurrence and detection by their estimated relative frequency and maintaining the categorical scoring of severity. In an example, the results of traditional FMEA of a near infrared (NIR) analytical procedure used for the screening of suspected counterfeited tablets are re-interpretated by this probabilistic modification of FMEA. Bahrami et al. (2012) proposed using of FMEA technique in the implementation and management of projects. The main end of this article is using FMEA technique in various stages of project implementation in order to systematically improvement of processes and reduces project costs. Xiao et al. (2011) extended the definition of *RPN* by multiplying it with a weight parameter, which characterise the importance of the failure causes within the system.

Mokhtari et al. (2012) used fuzzy set theory (FST) to describe and evaluate the associated risk factors within the ports and terminals operations and management (PTOM). An evidential reasoning (ER) approach is employed to synthesise the information produced. These processes constitute a decision support framework that will be used to conduct port-to-port risk evaluations or to assess a whole port's and terminal's overall risk level in order to facilitate continuous improvement strategies. Sofyalıoğlu and Kartal (2012) used a fuzzy analytic hierarchy process (FAHP) to determine the most important supply chain risks and the corresponding risk management strategies. The research is conducted with the supply chain management of a company operating in the iron and steel industry. Findings indicate that supply risks and operational risks are quite important compared to environmental risks. Wang and Sun (2012) discussed the risk evaluation index system of energy management contract project, proposed the analytic hierarchy process (AHP) and intuitionistic fuzzy sets to evaluate the risks of energy management contract project, then put up with a quantitative method for the energy management contract companies.

2 Fuzzy theory

Fuzzy set is used increasingly in recent researches because many aspects of phenomena are uncertain. This concept was presented by Zadeh (1971). FST has been attracted by a large number of researchers in different areas including risk management. The usual fuzzy risk evaluation methods can be divided into two categories, the rule-based inference methods and the mathematical calculation methods (Zhang and Chu, 2011). Chen and Chen (2007) presented a method for fuzzy risk analysis based on the ranking of generalised trapezoidal fuzzy numbers. Kangari and Riggs (1989) introduced a method for constructing risk assessment by linguistic terms. Schmucker (1984) applied a method for fuzzy risk analysis based on fuzzy number arithmetic operations. Carr and Tah (2001) investigated a fuzzy approach to construction project risk assessment and analysis. They described a hierarchical risk breakdown structure to represent a formal model for qualitative risk assessment. Antonelli et al. (2009) proposed a multi-objective evolutionary algorithm to generate Mamdani fuzzy rule-based systems with different good trade-offs between complexity and accuracy. Quek and Zhou (2001) represented a novel fuzzy network; the pseudo Quter-product-based fuzzy neural network (PQPFNN) and its two fuzzy-rule-identification algorithms.

A pure fuzzy logic system is formed by a set of the kind IF THEN to perform the tracing of the input universe $U \subset R^n$ on to the output universe $V \subset R$. Fuzzy rule number r is presented in the following way:

$$R^r = \text{if } x_1 \text{ is } \mu_{x_1}^r \text{ and } x_2 \text{ is } \mu_{x_2}^r \text{ and } x_3 \text{ is } \mu_{x_3}^r \text{ and} \ldots\ldots \text{and } x_n \text{ is } \mu_{x_n}^r, \text{ then } y \text{ is } \mu_y^r. \quad (1)$$

$\underset{\sim}{x} = (x_1, \ldots, x_n) \in U$ is input linguistic variable and $y \in V$ is output linguistic variable.

Where $\mu_{x_1}^r\ \mu_{x_2}^r\ \mu_{x_3}^r, \ldots, \mu_{x_n}^r$ and μ_y^r are the membership functions of $x_1, x_2, x_3, \ldots, x_n, y$. μ_y^r which is associated with the output of rule number r can be obtained using the minimum operation as follows:

$$\mu_{R^r}(x, y) = \mu_{x_1}^r \wedge \mu_{x_2}^r \wedge \mu_{x_3}^r \wedge \ldots \wedge \mu_{x_n}{}^r \quad (2)$$

To find the final result, fuzzy rule outputs can be aggregated by maximum operation as below:

$$\mu_R(x, y) = \vee_{r=1}^r R^r(x, y). \quad (3)$$

3 AHP and fuzzy AHP

AHP which was developed by Saaty (1980, 1999) is a multiple criteria decision-making technique utilising a pair-wise comparison approach. AHP with incorporate judgments on intangible qualitative criteria alongside tangible quantitative criteria solves many complicated decision-making problems (Pakdin, 2010). The following examples are about the application of AHP in project risk management process, Hastak and Shaked (2000) provided a structured approach for evaluating risk indicators involved in an international construction operation. It is designed to estimate the risk level of a specific project in a foreign country. Dikmen and Birgonul (2006) proposed a methodology for quantification of risks and opportunities associated with international projects. They used AHP in order to enable the decision-makers to compare attractiveness of alternative project options. Because of the uncertainty existing in the pair-wise comparison in AHP method, in many cases fuzzy AHP is used. Chang (1992), Cheng (1997), Deng (1999) and Mikhailov (2000) proposed some fuzzy AHP methods. In this study, we employ Mikhailov's fuzzy prioritisation approach.

4 FMEA and fuzzy FMEA

Risk analysis has considerable contribution in analytical validation to assess failures. FMEA is an important risk analysis tool which can be applied for better risk management. In fact, FMEA is a qualitative method that mitigates risks during the design phase before they occur. It first emerged from studies done by NASA in 1963.

There are different types of FMEA containing service FMEA, system FMEA, product/design FMEA, process FMEA and machine FMEA. The results of this analysis help managers and engineers to identify the failure modes and their causes and correct them during the stages of design and production. So, FMEA results a more effective risk management decision making (Chen et al., 2008; Ebrahimipour et al., 2010).

In fact, this method analyses potential reliability problems in the development cycle of the project, making it easier to take actions to overcome such issues, enhancing the reliability through design. So, it provides basic information for reliability prediction and product and process design (Ebrahimipour et al., 2010). Each FMEA includes the following items:

a failure mode

b failure cause

c failure effects

d detection methods (Guimarães and Lapta, 2004).

McDermott et al. (1996) described the detailed FMEA creation process. FMEA has been applied to different research areas including: the electrical design of automobile systems, Price et al. (1995); mechanical design, Hughes et al. (1999); hydraulic systems design, Atkinson et al. (1992) and Hogan et al. (1992).

RPN in traditional FMEA is used to evaluate risk by three criteria: occurrence (*O*), severity (*S*) and detection (*D*). The range of each criterion is scaled from 1 to 10. RPN can be used to rank the failure modes and is calculated by the following equation.

$$\text{RPN} = O \times S \times D \tag{4}$$

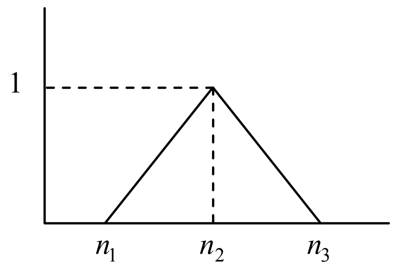
For the greater RPN value, the greater concern is needed. The occurrence is related to the probability of the failure mode. A '1' indicates the low probabilities and the '10' indicates the high probabilities. The severity denotes to the seriousness of the effects of a failure mode. A '1' indicates a failure does not affect anything and a '10' indicates a life threatening failure. The detection is concerned with the ability of identifying the occurrence of a potential cause of a failure mode. A '1' indicates a full ability of detection while a '10' indicates impossible detection (Garcia et al., 2005; Rhee and Ishii, 2003).

For prioritising failures in FMEA, researches employed a fuzzy logic-based approach. They used linguistic terms to describe O, S, D and the risks of failures to overcome limitations of the traditional RPN. Pillay and Wang (2003) proposed a fuzzy rule-based approach to avoid the use of traditional RPN. Bowles and Peláez (1995) used fuzzy if-then rules extracted from expert knowledge and expertise. Chang et al. (1999) applied gray relational analysis to determine the risk priority of potential causes. Ying-Ming et al. (2009) defined the FRPNs and used alpha-level sets and linear programming models in computation for ranking purpose. Xu et al. (2002) presented a fuzzy logic-based method for FMEA assessment by expert system for diesel engine's gas turbocharger to address the interdependencies among various failure modes with uncertain and imprecise information.

5 Mathematical notation of fuzzy set

A fuzzy set $\tilde{A}$ in a universe of discourse X is characterised by a membership function $\mu_{\tilde{A}}(x)$ which associates with each element x in X a real number in the interval [0, 1]. The function value $\mu_{\tilde{A}}(x)$ is termed the grade of membership of x in $\tilde{A}$. A triangular fuzzy number $\tilde{n}$ is displayed as (n_1, n_2, n_3) shown in Figure 1 (Kuafman and Gupta, 1991).

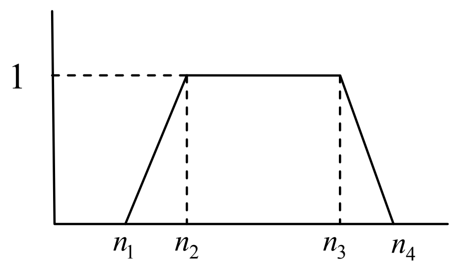
Figure 1 Triangular fuzzy number



Membership function $\mu_{\tilde{n}}(x)$ is defined as follows:

$$\mu_{\tilde{n}}(x) = \begin{cases} \dfrac{x-n_1}{n_2-n_1} & n_1 \le x \le n_2 \\ \dfrac{x-n_2}{n_3-n_2} & n_2 \le x \le n_3 \\ 0 & O.W \end{cases} \tag{5}$$

Figure 2 Trapezoidal fuzzy number



A trapezoidal fuzzy number (TrFN), which is shown in Figure 2, can be defined as $\tilde{m} = (a, b, c, d)$, where the memberships function $\mu_{\tilde{m}}$ of $\tilde{m}$ is given by:

$$\mu_{\tilde{m}}(x) = \begin{cases} \dfrac{x-a}{b-a} & (a \le x \le b) \\ 1 & (b \le x \le c) \\ \dfrac{d-x}{d-c} & (c \le x \le d) \end{cases} \tag{6}$$

Where [b, c] is called a mode interval of $\tilde{m}$, and a and d are called lower and upper limits of $\tilde{m}$, respectively. The results of fuzzy sum ⊕ and fuzzy subtract Θ for two triangular fuzzy numbers are triangular numbers while, the product ⊗ of two triangular numbers results in an approximately triangular number (Dubios and Prade, 1980). Consider two fuzzy numbers of $\tilde{n} = (n_1, n_2, n_3)$ and $\tilde{m} = (m_1, m_2, m_3)$ and a real positive number r. the product, sum and subtract of $\tilde{n}$ and $\tilde{m}$ are defined as follows:

$$\tilde{n} \oplus \tilde{m} = \left[n_1 + m_1, n_2 + m_2, n_3 + m_3\right] \tag{7}$$

$$\tilde{n} \Theta \tilde{m} = \left[n_1 - m_3, n_2 - m_2, n_3 - m_1\right] \tag{8}$$

$$\tilde{n} \otimes r = \left[n_1 r, n_2 r, n_3 r\right] \tag{9}$$

$$\tilde{n} \otimes \tilde{m} \approx \left[n_1.m_1, n_2.m_2, n_3.m_3\right]. \tag{10}$$

6 The proposed methodology

As mentioned, FMEA considers three factors including: risk severity, risk occurrence and risk not detection. In this paper, we take in to account these three factors. In addition, we consider two more factors in the proposed methodology: the weights of risks and the weights of project life cycle phases. These two factors have been referred by other researchers as important contributing factors in risk evaluation (Xie et al., 2006). As the first three factors are often described qualitatively, we use fuzzy rules.

Stages of a project risk management process are shown in Figure 3. Our proposed method, covers stages 1, 2, 4 and 5 of a project risk management process, is illustrated in Figure 4, schematically.

Step 1 Identify the project life cycle phases: There is no single best way to define the ideal project life cycle. Some organisations have established policies that standardise all projects with a single life cycle, while others allow the project management team to choose the most appropriate life cycle for the project (PMBOK, 2004).

Step 2 Identify project risks in the risk breakdown structure framework.

Step 3 Assign an occurrence number $(\tilde{O})$ for each risk found in risk breakdown structure for each project life cycle's phase.

Step 4 Assign a severity number $(\tilde{S})$ of each risk found in risk breakdown structure for each project life cycle's phase.

Step 5 Assign a not detection number $(\tilde{D})$ of each risk found in risk breakdown structure for each project life cycle's phases.

Step 6 Calculate the fuzzy RPN_{ijl} for the i^{th} sub risk of l^{th} major risk in j^{th} project phase by using equation (11).

$$R\tilde{P}N_{ijl} = \tilde{O} \otimes \tilde{S} \otimes \tilde{D} \tag{11}$$

Step 7 Calculate the weights of subrisks (W_{il}) by Mikhailov's AHP method.

Step 8 Assign a weight to each project life cycle phase by equation (12) (Xie et al., 2006).

$$\alpha_j = 1/j \tag{12}$$

Step 9 Calculate final RPN of each major risk based on equation (13).

$$\begin{aligned} RPN_i &= W_{il} \times RPN_{ijl} \times \alpha_j \qquad && i \in I \\ RPN_l &= \sum_{i \in I} \sum_{j \in J} W_{il} \times RPN_{ijl} \times \alpha_j \qquad && l \in L \end{aligned} \tag{13}$$

for

L number of major risk

J number of project phase

I number of subrisk.

Step 10 Define a fuzzy membership function for final RPN of each major risk based on linguistic variables such as very low (VL), low (L), medium (M), high (H) and very high (VH). Membership function of project risk magnitude is also defined as negligible (N), minor (Mi), major (Ma) and critical (C). Final RPN of each major risk is evaluated by using these defined membership functions.

Step 11 Use the fuzzy logic represented in Section 2 to define fuzzy rules. These rules are presented by experts' judgment about the relation between inputs and output in an if-then rules form.

Step 12 Determine the project risk magnitude by using fuzzy logic defined in equations (2) and (3) and defuzzify the obtained fuzzy number by using following equation.

$$DF = \left(\sum_{i=1}^{q} Y_i \mu_R(x, y) \right) \Bigg/ \left(\sum_{i=1}^{q} \mu_R(x, y) \right). \tag{14}$$

Then, propose the appropriate response for risk. We define four types of responses: 'risk prevention (RP)', 'risk transmission (RT)', 'RISK reduction (RR)' and 'risk adaption (RA)'. Based on the project risk magnitude, we choose the appropriate response. More specifically, we find the intersection point between the project risk magnitude and project risk response membership functions and then the associated risk response with the intersection point is chosen.

Figure 3 Project risk management process according to PMBOK (see online version for colours)

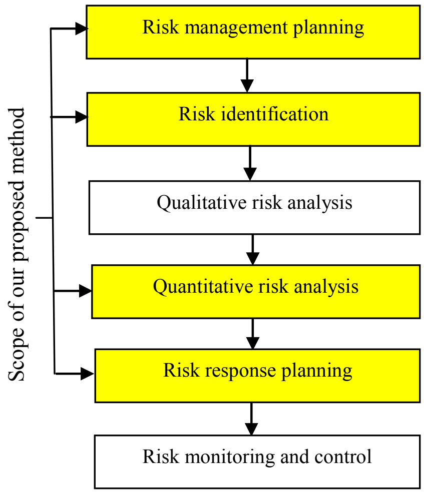
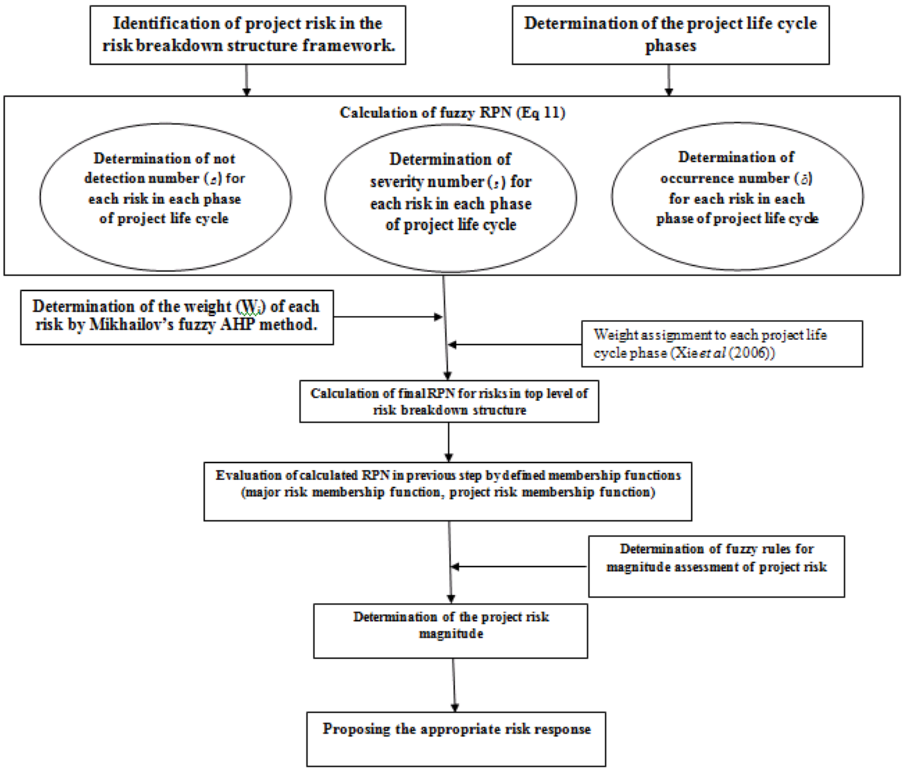


Figure 4 Steps of our method



7 Case study

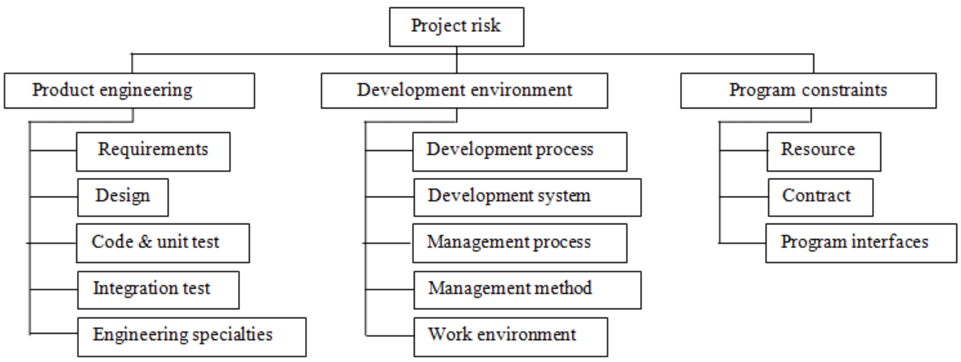
The case study for the application of our proposed model is a given construction company 'A' with the intention of assembly and production of road construction equipment which gradually engaged in fabrication of parts and components for industrial projects, as power stations, oil, gas and petrochemical complexes, portal cranes, etc. The linguistic variables are presented in Table 1.

Table 1 Linguistic variables for severity, occurrence and not detection of the risks

Very low (VL)	(1, 2, 3)
Low (L)	(2, 4, 6)
Medium (M)	(4, 6, 8)
High (H)	(6, 8, 9)
Very high (VH)	(8, 9, 10)

- *Steps 1, 2:* The phases of project life cycle, risks and sub-risks which are used in the model are determined by an expert team. Figure 5 shows the risk breakdown structure.

Figure 5 Risk breakdown structure



The project life cycle phases are presented in Table 2.

Table 2 Project life cycle phases

	Project phases
1	Initiation
2	Planning
3	Execution
4	Monitoring and control
5	Closure

- *Steps 3, 4, 5:* The expert team assigns the severity, occurrence and not detection to each risk during project life cycle as shown in Table 3. Linguistic variables described in Table 1 are used to form Table 3.

Table 3 Assignment of severity, occurrence and not detection of each risk

Project phases / *Risk items*	*Initiation*			*Planning*			*Execution*			*Monitoring and control*			*Closure*		
	O	*S*	*D*	*O*	*S*	*D*	*O*	*S*	*D*	*O*	*S*	*D*	*O*	*S*	*D*
Product engineering															
Requirements	L	L	H	L	L	H	M	M	L	H	M	H	VH	VH	VL
Design	VL	VH	VH	M	VL	VH	VH	M	H	H	H	M	VH	VH	VL
Code and unit test	L	L	VH	VL	VL	VH	M	VH	H				VH	M	L
Integration test	VL	L	VH				VH	L	VH	VH	M	VH	VH	VH	L
Engineering specialties	L	M	H				H	L	H	H	VH	M	VH	VH	L
Development environment															
Development process	VL	L	VH				VH	M	H	H	H	M	VH	VH	H
Development system	L	H	VH				H	M	H	H	VH	M	H	VH	L
Management process	M	H	M	H	H	L	H	VH	L	VH	VH	VL	VH	VH	L
Management methods	M	H	VH		L		H	H	VH	H	M	L	VH	VH	VL
Work environment	H	VL	M	H	L	H	H	H	M	VH	H	L	VH	M	L
Program constraints															
Resources	M	M	M	M	M	M	M	H	M	VH	VH	M	VH	VH	H
Contract	M	H	H	H	H	H				VH	VH	H	VH	VH	L
Program interfaces				M	M	M	L	M	M	M	H	L	VH	VH	H

Table 4 Calculated RPN_{ijl} for each risk

Risk items \ *Project phases*	*Initiation*			*Planning*			*Execution*			*Monitoring and control*			*Closure*		
	$RPN_{i1l} = (a, b, c)$			$RPN_{i2l} = (a, b, c)$			$RPN_{i3l} = (a, b, c)$			$RPN_{i4l} = (a, b, c)$			$RPN_{i5l} = (a, b, c)$		
Product engineering															
Requirements	24	128	324	24	128	324	32	144	384	144	384	648	64	162	300
Design	64	162	300	32	108	240	192	432	720	144	384	648	64	162	300
Code and unit test	32	144	360	8	36	90	192	432	720	0	0	0	96	288	540
Integration test	16	72	180	0	0	0	128	324	600	256	486	800	128	324	600
Engineering specialties	48	192	432	0	0	0	72	256	486	96	288	540	128	324	600
Development environment															
Development process	16	72	180	0	0	0	192	288	576	144	384	648	384	648	900
Development system	96	288	540	0	0	0	144	384	648	192	432	720	96	288	540
Management process	96	288	576	72	256	486	96	288	540	64	162	300	128	324	600
Management methods	192	432	720	0	0	0	288	576	810	48	192	432	64	162	300
Work environment	36	128	243	72	256	486	144	384	648	96	288	540	64	216	480
Program constraints															
Resources	64	216	512	64	216	512	96	288	576	256	486	800	384	648	900
Contract	144	384	648	216	512	729	0	0	0	384	648	900	128	324	600
Program interfaces	0	0	0	64	216	512	32	144	384	48	192	432	384	648	900

- *Step 6:* RPN of each sub risk in each phase of project life cycle is calculated according to equation (11). The results are shown in Table 4.
- *Step 7:* Now we determine the importance weights of sub risk using Mikhailov's fuzzy AHP method. The result of this step is shown in Table 5.

Table 5 Risk item weight

Risk item weight	
Product engineering	
Requirements	0.08
Design	0.1
Code and unit test	0.05
Integration test	0.05
Engineering specialties	0.05
Development environment	
Development process	0.05
Development system	0.11
Management process	0.19
Management methods	0.1
Work environment	0.09
Program constraints	
Resources	0.12
Contract	0.01
Program interfaces	0.01

- *Step 8:* We assign weights to each project life cycle phase using equation (12). The obtained weights are shown in the second row of Table 6 (α_j).
- *Step 9:* applying equation (13) leads to final RPN for each sub risks as shown in Table 6 (RPN_i) and Table 7 is final RPN for major risks (RPN_l).
- *Step 10:* As we mentioned in Step 10, membership of major risk's final RPN are as shown in Figure 6. As illustrated in Figure 6, the intersection between the final RPN of major risks and the membership function of them are determined.

  These are the results of these intersections:

  - *development environment risk:* ((VL, 0.4437), (L, 1), (M, 0.6295), (H, 0.0753))
  - *program constraint:* ((VL, 1), (L, 0.1649))
  - *product engineering:* ((VL, 1), (L, 0.4881)).

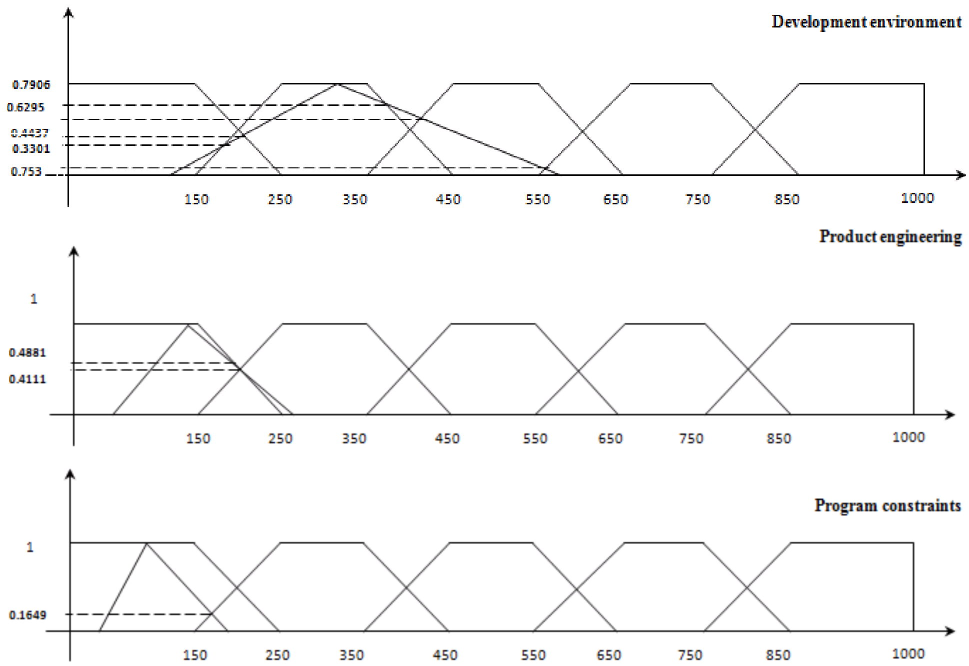
Table 6 Final RPN_i for each risk

Risk items \ *Project phases*	*Initiation*			*Planning*			*Execution*			*Monitoring and control*			*Closure*		
α_j	*1*			*1/2*			*1/3*			*1/4*			*1/5*		
	$RPN_i = (a, b, c)$			$RPN_i = (a, b, c)$			$RPN_i = (a, b, c)$			$RPN_i = (a, b, c)$			$RPN_i = (a, b, c)$		
Product engineering															
Requirements	1.9	10.2	25.9	1.0	5.1	13.0	0.9	3.8	10.2	2.9	7.7	13.0	1.0	2.6	4.8
Design	6.4	16.2	30.0	1.6	5.4	12.0	6.4	14.4	24.0	3.6	9.6	16.2	1.3	3.2	6.0
Code and unit test	1.3	5.8	14.4	0.2	0.7	1.8	2.6	5.8	9.6	0.0	0.0	0.0	0.8	2.3	4.3
Integration test	0.8	3.6	9.0	0.0	0.0	0.0	2.1	5.4	10.0	3.2	6.1	10.0	1.3	3.2	6.0
Engineering specialties	2.4	9.6	21.6	0.0	0.0	0.0	1.2	4.3	8.1	1.2	3.6	6.8	1.3	3.2	6.0
Development environment															
Development process	0.8	3.6	9.0	0.0	0.0	0.0	3.2	4.8	9.6	1.8	4.8	8.1	3.8	6.5	9.0
Development system	10.6	31.7	59.4	0.0	0.0	0.0	5.3	14.1	23.8	5.3	11.9	19.8	2.1	6.3	11.9
Management process	18.2	54.7	109.4	6.8	24.3	46.2	6.1	18.2	34.2	3.0	7.7	14.3	4.9	12.3	22.8
Management methods	19.2	43.2	72.0	0.0	0.0	0.0	9.6	19.2	27.0	1.2	4.8	10.8	1.3	3.2	6.0
Work environment	3.2	11.5	21.9	3.2	11.5	21.9	4.3	11.5	19.4	2.2	6.5	12.2	1.2	3.9	8.6
Program constraints															
Resources	7.7	25.9	61.4	3.8	13.0	30.7	3.8	11.5	23.0	7.7	14.6	24.0	9.2	15.6	21.6
Contract	1.4	3.8	6.5	1.1	2.6	3.6	0.0	0.0	0.0	1.0	1.6	2.3	0.3	0.6	1.2
Program interfaces	0.0	0.0	0.0	0.3	1.1	2.6	0.1	0.5	1.3	0.1	0.5	1.1	0.8	1.3	1.8

Table 7 Final RPN for major risks

Major risk	*Final RPN*
Product engineering	(45.18, 131.88, 262.65)
Development environment	(117.33, 316.31, 577.17)
Program constraints	(37.31, 92.54, 181.10)

Figure 6 Membership of major risk's final RPN



- *Step 11:* As each major risk's final RPN has five linguistic variables, the total number of rules is 5×5×5 = 25. We define 80 rules in this case study. Two samples of our rules are as follows:

  a R^1 = if 'development environment risk' is low (L), 'program constraint' is very low (VL) and 'product engineering' is very low (VL), then project risk magnitude is negligible (N).

  b R^2 = if 'development environment risk' is medium (M), 'program constraint' is very low (VL) and 'product engineering' is very low (VL), then project risk magnitude is minor (Mi).

- *Step 12:* We now use equation (2) and the mentioned fuzzy rules to obtain the outputs in Table 8.

Table 8 Fuzzy logic results (see online version for colours)

Development environment risk	*Program constraint*	*Product engineering*	
		VL(1)	*L(0.4881)*
VL(0.4437)	VL(1)	N(0.4437)	Mi(0.4437)
	L(0.1649)	N(0.1649)	Mi(0.1649)
L(1)	VL(1)	N(1)	Mi(0.4881)
	L(0.1649)	Mi(0.1649)	Mi(0.1649)
M(0.6295)	VL(1)	Mi(0.6295)	Mi(0.4881)
	L(0.1649)	Mi(0.1649)	Mi(0.1649)
H(0.0753)	VL(1)	Mi(0.0753)	Ma(0.0753)
	L(0.1649)	Ma(0.0753)	Ma(0.0753)

For example, the following statement clarifies how the highlighted cell in Table 8 is calculated:

$$\begin{aligned}\mu_{R^2} &= \mu_M\,(\text{development environment risk})\\ &\quad \wedge \mu_{VL}\,(\text{program constraint})\\ &\quad \wedge \mu_{VL}\,(\text{product engineering})\\ &= \min(0.6295, 1, 1) = \mu_{Mi}\,(\text{project risk magnitude}) = 0.6295\end{aligned}$$

Now, the project risk magnitude can be obtained based on equation (3), using the maximum rule. The results show that the project risk magnitude is:

for N: $\mu\text{N} = \max(0.4437, 0.1649, 1) = 1$

for Mi: $\mu\text{Mi} = \max(0.1649, 0.6295, 0.0753, 0.4437, 0.4881) = 0.6295$

for Ma: $\mu\text{Ma} = \max(0.0753) = 0.0753$

so,

$$\big((1, \mu N(\text{project risk magnitude})\big),$$
$$\big(0.6295, \mu Mi(\text{project risk magnitude})\big),$$
$$\big(0.0753, \mu Ma(\text{project risk magnitude})\big).$$

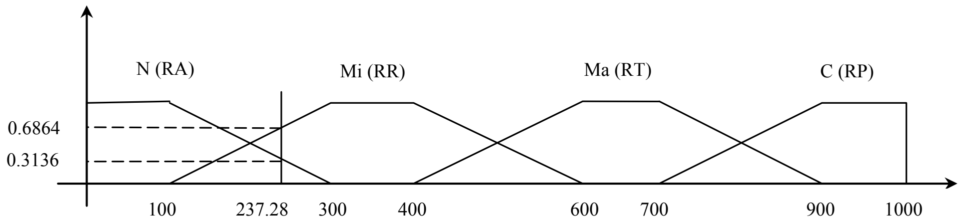
Then, we should defuzzify the above result by equation (14).

$$\text{defuzzified value of the project risk magnitude}:$$
$$= \frac{100 \times 1 + 400 \times 0.6295 + 700 \times 0.0753}{1 + 0.6295 + 0.0753} = 237.28$$

The obtained value for the project risk magnitude (237.28) is converted to a value in scale (0–1) as shown in Figure 7. The project risk is negligible with 31.36% and minor with 68.64%.

According to the project risk magnitude, as 68.64% is minor, so we should have risk reduction as response (Figure 7).

Figure 7 Project risk magnitude membership function



8 Conclusions

In this paper, we presented a new methodology that covers four phases of risk management process namely, risk management planning, risk identification, quantitative risk analysis and risk response planning. The approach is original as it considers two new factors contributing risk evaluation: the weights of risks and the weights of project life cycle phases in addition to risk severity, risk occurrence and risk not detection. The project risk magnitude, which is obtained by the proposed model, determines the appropriate risk response. The given company demonstrates how the new methodology can be employed.

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