*Iranian Journal of Management Studies (IJMS)* *http://ijms.ut.ac.ir/*
*Vol. 8, No. 3, July 2015* *Print ISSN: 2008-7055*
*pp: 373-395* *Online ISSN: 2345-3745*

# Using fuzzy FMEA and fuzzy logic in project risk management

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(Received: 6 March, 2014; Revised: 23August, 2014; Accepted: 26August, 2014)

## Abstract

Risk management is one of the most important phases of project management and is the most recently used by many researchers. In this paper, a fuzzy based method was proposed which identifies different kinds of risks through the project life cycle. Then, the project risk magnitude can be obtained in regards to five factors, namely “severity”, “occurrence”, and “not detection” which form fuzzy FMEA and also two other factors namely project phase weights and risks weights. These two factors in addition to risk priority number (RPN) factors can lead to the application of better risk management. Based on the project risk magnitude, the appropriate risk response should be selected. The proposed model covers three parts of risk management process: 1. Risk identification, 2. Quantitative risk analysis and 3. Risk response planning. Finally, this model was applied by a numerical example, and project risk magnitude was calculated for an assumed company, to verify the proposed method.

## Keywords

Analytical Hierarchy Process, Failure Mode and Effects Analysis (FMEA), Fuzzy Rules, Project Risk Management.

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## Introduction

According to the project management body of knowledge (PMBOK2004) definition, a project is a temporary endeavor undertaken to create a unique product or service. Construction projects are perceived to have more inherent risks, due to the involvement of many contracting parties such as owners, designers, contractors, subcontractors, suppliers, etc., in addition to the economic, political, social and cultural conditions, where the project is to be undertaken (Jomaah *et al.*, 2010).

Fuzzy logic is a very appropriate method for project risk assessment and for dealing with uncertainty and fuzziness in human decision making. Many approaches have been suggested in using fuzzy logic in risk assessment of projects. Zeng *et al.* (2007) applied fuzzy set theory to evaluate the performance of cost and time in management of construction project's risk management and utilization. Kuchta (2001) applied fuzzy numbers in the risk evaluation of construction projects.

The objective of this research was to use fuzzy Failure Mode and Effects Analysis (FMEA) concept in project risk assessment, to decrease errors of risk factors in risk management decision making. The proposed method uses AHP and FMEA approaches to present an accurate framework which considers project life cycle weights and risk weights in the risk assessment process. This method calculates project risk magnitude considering the factors of risk priority number (RPN) that has not been used in other researches. This factor evaluates risk by three criteria namely "severity", "occurrence", and "not detection". However, current researches have not considered such precision components of risk assessment in details.

The rest of the paper is organized as follows. Section 2 presents an overview of the literature project risk management, fuzzy theory, AHP and FMEA. In Section 3, the proposed method and its steps are presented in details. How the proposed model is used on a real world example is explained in Section 4 by a numerical example. Finally, in Section 5 conclusions are discussed.

## Literature Review

### Project risk management

Project risk management is an endeavor to increase the probability and impact of positive events and decrease the probability and impact of events adverse to the project. This approach is concerned with conducting risk management planning, risk identification, qualitative risk analysis, quantitative risk analysis, risk response planning, as well as risk monitoring and control on a project (Elgembri & Altamimi, 2011). These phases are described below briefly (PMBOK, 2004).

**Risk management planning** is the process of deciding how to approach and conduct the risk management activities for a project. Its tool is planning meeting and analysis.

**Risk identification** determines which risks might affect the project, and documents their characteristics. Its tools includes documentation reviews, information gathering techniques, checklist analysis, assumption analysis, and diagramming techniques.

**Qualitative risk analysis** includes methods for prioritizing the identified risks for further action, such as quantitative risk analysis or risk response planning. Its tools are risk probabilities and impact assessment, probability and impact matrix, risk data quality assessment, risk categorization and risk urgency assessment.

**Quantitative risk analysis** is performed on risks that have been prioritized by the qualitative risk analysis process as potentially and substantially impacting the project's competing demands. Its tools are data gathering, representation techniques, quantitative risk analysis and modeling techniques.

**Risk response planning** is the process of developing options, and determining actions to enhance opportunities and reduce threats to the project's objectives. Its tools are strategies for negative risks or threats, strategies for positive risks or opportunities, strategy for both threats and opportunities and contingent response strategy.

**Risk monitoring and controlling** is the process of identifying, analyzing, and planning for newly arising risks, keeping track of the identified risks and those on the watch list, reanalyzing existing risks, monitoring trigger conditions for contingency plans, monitoring residual risks, and reviewing the execution of risk responses while evaluating their effectiveness. Its tools are risk reassessment, risk audits, variance and trend analysis, technical performance measurement, reserve analysis and status meeting.

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 centers 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 on the various factors spanning all phases of the project life cycle. Formal risk management process (RMP) should be applied at all stages in the project life cycle and should consider several potential aspects such as the technology, market, financial, operational, organizational, and business. This ensures 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 probably concerned with more than one phase. Many researchers have focused on risk management in a particular project phase.

Jaafari (2001) proposed a case for a shift to strategy-based project management, a component of which is real time management of risks, uncertainties and opportunities using a life cycle project management approach. Jaffari stated that risk management should form a core function of this strategy-based project management approach, using life cycle objective functions as the main drivers for risk reduction and value addition.

Sharratt and Choong (2002) proposed a methodology to recognize and assess the risks in a project which arise from environmental issues. They used a life-cycle framework to identify the mass and energy flows associated with activities throughout the project and their relevant environmental problems.

Patrick *et al.* (2007) stated the risks relative to different phases of the project, which are briefly as follows:

- Feasibility phase: Most risks at this stage are related to clients and governmental agencies.
- Design phase: Designers play the most important role in this phase. They should make every effort to fully understand the wants and needs of clients.
- Construction phase: Most risks in the construction phase are likely to rest with contractors and subcontractors.

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. These researchers analyzed the possible risk response measures for various risk categories and the corresponding strength of the measures. In their research, a team consisting of experts and stakeholders achieved consensus on identifying the risks existing at the time, evaluating the risk and scoring the risk exposure (RE) of software projects and the related risk items. When risk avoidance decision-making occurs in the *k*th stage, cumulative RE of the risk factor i is defined as:

$$RE_i = \sum_{j=k}^{m} \alpha_i RE_{ij} \quad (1)$$

where $\alpha_i$ denotes the weight of $RE_{ij}$ and

$$\alpha_i = 1/(j-1) \quad (2)$$

The integrative risk exposure (IRE) of the *t*th risk category and IRE of the project are respectively defined as:

$$IRE_t = \sum_{i=1}^{n_t} RE_i \quad (3)$$

$$IRE = \sum_{i=1}^{n} RE_i \quad (4)$$

IRE was used to decide the risk avoidance strength of risk categories and the project, respectively. Based on IRE t and IRE, bid/no-bid policy, risk response measures and corresponding strengths were taken into account, in order to reduce the bidding risk.

Despite the importance of the response phase in reducing the likelihood of risk occurrence and/or the magnitude of their negative impact, this phase has not received attention in project risk research.

Some studies have been conducted in risk response as follows, DSMC (1986) reviewed examples of risk handling in weapon development projects, Tsai (1992) interviewed management in weapon development projects and proposed seven risk-handling strategies. The method proposed in this study uses four responses based on project risk magnitude such as risk prevention, risk transmission, risk reduction and risk adaption in the risk response planning phase. Considering uncertainty and fuzziness, as developed in the structure of the proposed method, results in a more accurate calculation of risk magnitude and subsequently results in choosing a more appropriate response.

### Fuzzy theory

Zadeh (1965) introduced the fuzzy set theory to deal with uncertainty due to imprecision and vagueness. A major contribution of fuzzy set theory is its capability of representing vague data. Fuzzy set theory has been applied to many areas which need to manage uncertain and vague values such as risk management. The usual fuzzy risk evaluation methods can be divided into two categories; 1. The rule-based inference method and 2. The mathematical calculation method (Zhang & Chu, 2011).

There is a variety of tools that can be used to communicate identified risks to project stakeholders. These tools include the risk list, risk matrix, risk map and RBS (PMI, 2008; Raz & Michael, 2001; Macgill & Siu, 2005). Carr and Tah (2001) in their paper, investigated a fuzzy approach to construct project risk assessment and analysis. In this paper, a hierarchical risk breakdown structure has been described to represent a formal model for qualitative risk assessment. In this part, some basic fuzzy rules concepts which are applicable for the proposed method were reviewed as follows:

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 $V \subset R$. The *r*th fuzzy rule is presented in the following way:

$$R^r = if\ x_1\ is\ \mu_{x_1}^r\ and\ x_2\ is\ \mu_{x_2}^r\ and\ x_3\ is\ \mu_{x_3}^r\ then\ y\ is\ \mu_y^r \quad (5)$$

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

Where $\mu_{x_1}^r \mu_{x_2}^r \mu_{x_3}^r$ and $\mu_y^r$ are the membership functions of $x_1$, $x_2$, $x_3$, and y. The $\mu_y^r$ $r$th rule output can be obtained using minimum operation as below:

$$\mu_{R^r}(x, y) = \mu_{x_1}^r \wedge \mu_{x_2}^r \wedge \mu_{x_3}^r \quad (6)$$

Fuzzy rule outputs can be aggregated by maximum operation as below:

$$\mu_R(x, y) = \vee_{r=1}^{r} R^r(x, y) \quad (7)$$

**Analytical hierarchy process (AHP) and fuzzy AHP**

The AHP was developed by Saaty (1980, 1999), and it is a multiple criteria decision-making technique based on a pair-wise comparison approach. The AHP incorporates judgments on intangible qualitative criteria alongside tangible quantitative criteria and solves many complicated decision-making problems (Badri, 2001; Chan & Kumar, 2007; Dagdeviren & Yüksel, 2008; Kahraman *et al.*, 2003; Kulak *et al.*, 2005). 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 the quantification of risks and opportunities associated with international projects using AHP, so that the decision-maker may compare the attractiveness of alternative project options. As a result of the uncertainty existing in the pair-wise comparison in the AHP method, in many cases fuzzy AHP is used. The following researchers Cheng (1997), Deng (1999) and Mikhailov (2000) proposed some fuzzy AHP methods. In this study, Mikhailov’s fuzzy prioritization approach is preferred.

Mikhailov proposed a fuzzy programming method (FPM) based on the geometrical representation of the prioritization process.

This method transforms the prioritization problem into a fuzzy programming problem that can easily be solved as a standard linear program. He defined the measure of intersection μ of m fuzzy lines based on triangular fuzzy numbers suggested by Zimmermann as:

$$\mu = \max_w \left[ min\left\{ \left(1 - \frac{R_1 w}{d_1^+}\right), \left(1 - \frac{R_1 w}{d_1^-}\right), \ldots \times \left(1 - \frac{R_m w}{d_m^+}\right), \left(1 - \frac{R_m w}{d_m^-}\right) \right\} \right] \quad (8)$$

where the normalization condition $\sum_{i=1}^{n} w_i = 1$ is satisfied. Therefore, the formulation of the max-min problem is equivalent to the following linear program:

$$max\ \mu \quad (9)$$

Subject to:

$$\mu d_j^+ + R_j w \leq d_j^+$$
$$\mu d_j^- - R_j w \leq d_j^- \; j=1,2,\ldots m$$
$$\sum_{i=1}^{n} w_i = 1\ ,\ w_i \geq 0 \; i=1,2,\ldots,n$$

where the values of the left and right tolerance parameters $d_j^-$ and $d_j^+$ represent the admissible interval of approximate satisfaction of the crisp equality $R_j w = 0$ on the simplex hyperplane. The FPM transforms the prioritization problem into the linear program (9) that can easily be solved by the standard simplex method.

**Failure mode and effects analysis (FMEA) and fuzzy FMEA**

Risk analysis has considerable added value in analytical validation to assess failures, and 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.

The results of FMEA enable managers and engineers to identify the failure modes and their causes, and then correct them during the stages of design and production. So, it results in an easier risk management decision making (Chen *et al.*, 2008; Ebrahimipour *et al.*, 2010). Indeed, this method analyzes the 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. Therefore, it provides basic information for reliability prediction, as well as product and process design (Ebrahimipour *et al.*, 2010; Puente *et al.*, 2002; Sharma *et al.*, 2008).

Each FMEA included the following items:

a) Failure Mode

b) Failure Cause

c) Failure Effects

d) Detection Methods (Guimarães *et al.*, 2004).

Risk priority number (RPN) is a technique used for analyzing the risks associated with potential problems identified during a FMEA. RPN in traditional FMEA is used to evaluate risk by three criteria:

1. Occurrence (O),
2. Severity (S), and
3. 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 following equation.

$$\text{RPN} = O \times S \times D. \qquad (10)$$

For greater RPN value, greater considerations are needed. The occurrence is related to the probability of the failure mode. A '1' indicates low probabilities and '10' indicates high probabilities. The severity is related 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 related to the power identifying the occurrence of a potential cause of a failure mode. A '1' indicates certain to be detected and a '10' indicates impossible to detect (Arabian-Hoseynabadi *et al.*, 2010; Garcia *et al.*, 2005; Rhee *et al.*, 2010).

Many researches have described a fuzzy logic based approach for prioritizing failures in a system FMEA. They used linguistic terms to describe O, S, D, and the risks of failures for overcoming the shortcomings of the traditional RPN.

Pillay and Wang (2003) proposed a fuzzy rule based approach to avoid the use of traditional RPN. Xu *et al.* (2002) presented a fuzzy logic base method for the FMEA assessment expert system for diesel engine's gas turbocharger to address the interdependencies among various failure modes with uncertain and imprecise information. Braglia *et al.* (2003b) proposed a multi-attribute decision-making approach called fuzzy TOPSIS approach for FMECA, which is a fuzzy version of the technique TOPSIS.

Ying-Ming *et al.* (2009) defined the FRPNs and used alpha-level sets and linear programming models in their computation for ranking purpose.

## Proposed methodology

According to PMBOK (2004), the project risk management process includes the following stages. In this paper, our proposed method which covers stages 2, 4 and 5, is represented.

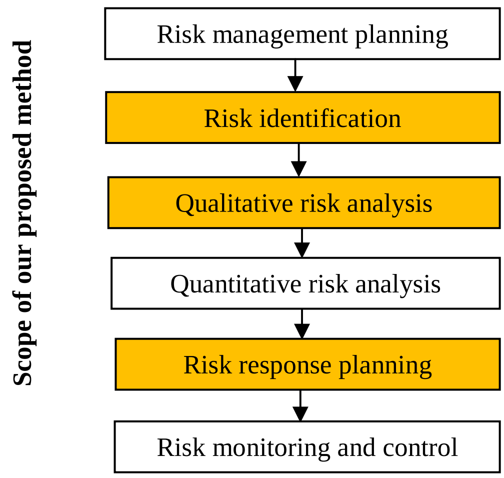


**Fig. 1. Project risk management process according to PMBOK**

The steps of our method are as follows:

**Step 1:** Determination of the project life cycle phases. There is no single best way to define the ideal project life cycle. Some organizations have established policies that standardize 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:** Identification of project risk in the risk breakdown structure framework.

**Step 3:** Determination of the occurrence number ($\tilde{O}$) of each risk in the risk breakdown structure for each project life cycle's phases.

**Step 4:** Determination of the severity number ($\tilde{S}$) of each risk in the risk breakdown structure for each project life cycle's phases.

**Step 5:** Determination of the not detection number ($\tilde{D}$) of each risk in the risk breakdown structure for each project life cycle's phases. Here "not detection" means that the risks are not discoverable.

**Step 6:** Calculation of fuzzy RPN using equation 11.

$$\widetilde{RPN} = \tilde{O} \times \tilde{S} \times \tilde{D} \qquad (11)$$

**Step 7:** Determination of the weights of the *i*th sub risk ($W_i$) of each risk in the risk breakdown structure by Mikhailov's AHP method.

**Step 8:** Weight Assignment to each project life cycle phase using equation 12 which is represented in reference (Xie *et al.,* 2006).

$$\alpha_i = 1/(j-1) \qquad (12)$$

**Step 9:** Calculation of final RPN of each major risk based on equation (13).

$$RPN_l = \sum_{i \in I} \sum_{j \in J} W_{il} \times RPN_{ijl} \times \alpha_j \quad l \in L \qquad (13)$$

*For L=number of major risk*
*J=number of project phase*
*I=number of subrisk*

**Step 10:** Definition of fuzzy membership functions for each major risk's final RPN is as very low (VL), low (L), medium (M), high (H) and very high (VH). Project risk magnitude is also defined as negligible (N), minor (Mi), major (Ma) and critical (C). Then evaluation of each major risk's final RPN was performed using these membership functions.

**Step 11:** Using the fuzzy theory represented in section 2.2 to define fuzzy rules. These rules are presented by experts' judgment about the relation between inputs and output in a form of if-then rules.

**Step 12:** Determination of the project risk magnitude. Defuzzification of this result can be calculated by equation (14).

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

**Step 13:** Proposing the appropriate response for risk.

We have defined four responses as fuzzy sets which were shown in below**:**

- Risk adaption (RA) : (0, 100, 300)
- Risk reduction (RR) : (100, 300, 400, 600)
- Risk transmission (RT) : (400, 600, 700, 900)
- Risk prevention (RP) : (700, 900, 1000)

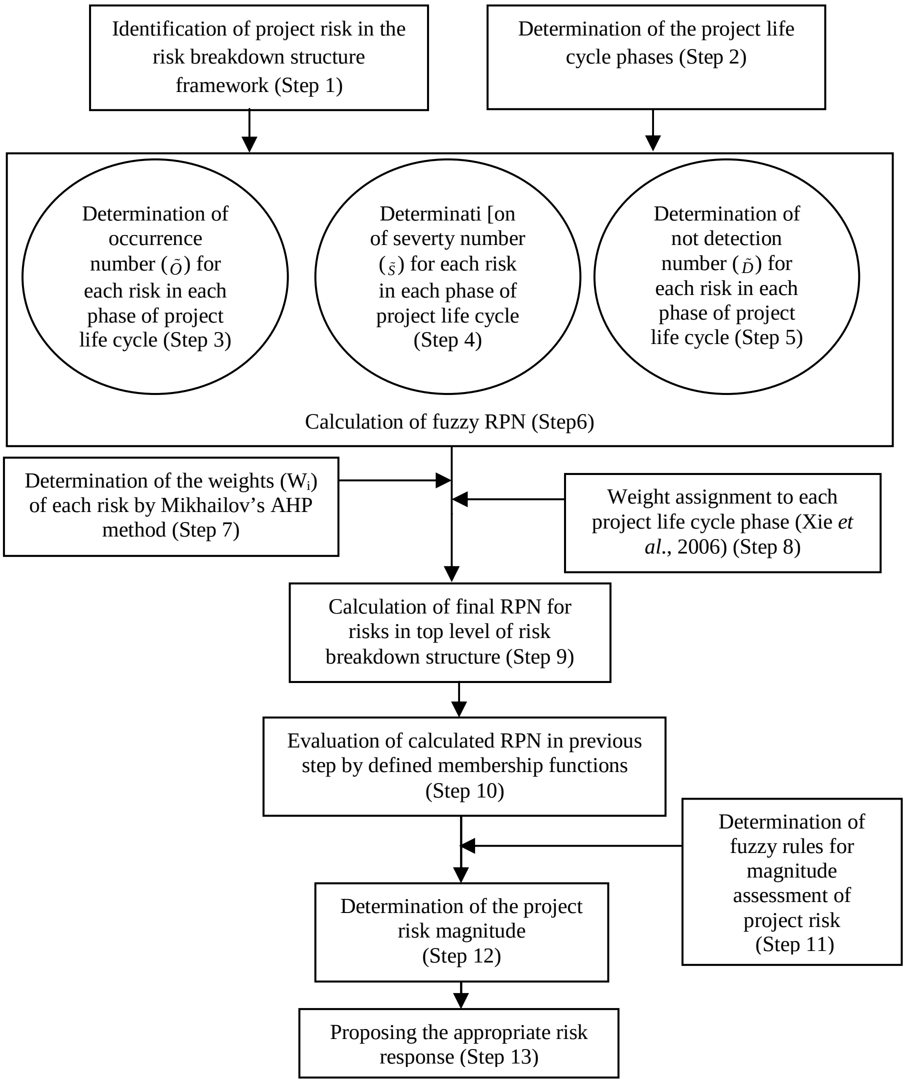


**Fig. 2. Steps of the proposed method**

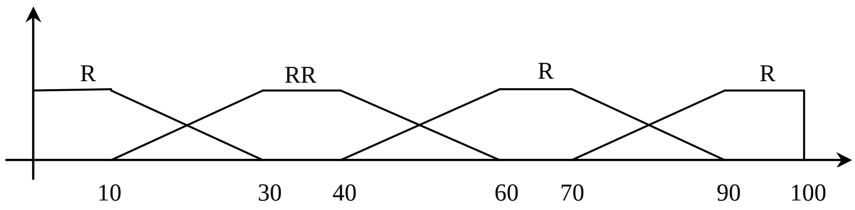


**Fig. 3. project risk response**

So based on the situation of the project risk magnitude, the appropriate response will be selected.

## Numerical Example

In this section, the information of a construction company “A” was considered, in order to apply the proposed model by a numerical example. For this purpose, an expert team consisting of four managers of the company and the authors of this paper were organized.

The linguistic variables used in this paper are presented in Table 1.

**Table 1. Linguistic Triangular Fuzzy Scale**

| Linguistic scale | Triangular Fuzzy numbers |
|---|---|
| Very low(VH) | (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 and 2:** The phases of project life cycle, risks and sub-risks to be used in the model are determined by the expert team. Figure 4 shows the risk breakdown structure.

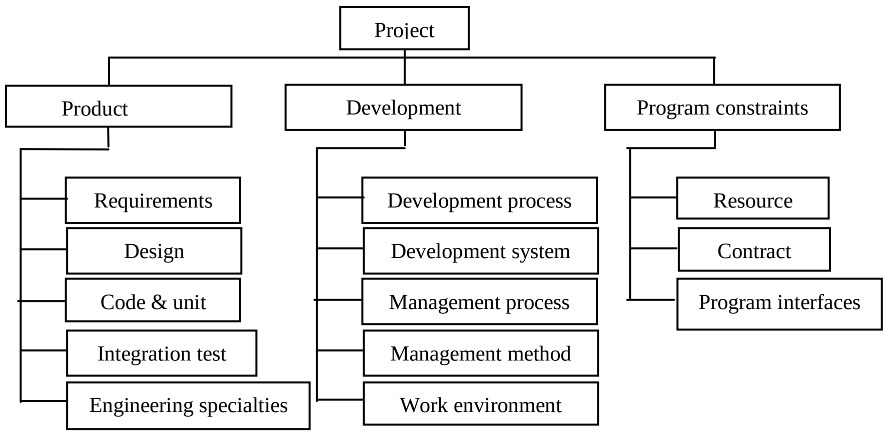


**Fig. 4. Risk breakdown structure**

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 & control |
| 5 | Closure |

**Steps 3, 4, 5:** Assignment of “severity”, “occurrence”, and “not detection” to each risk during project life cycle is in Table 3. The linguistic variables described in Table 1 are used here.

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

| Project phases / Risk items | Initiation | | | Planning | | | Execution | | | Monitoring & 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 & 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 |
| Develoment 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 |

**Step6:** calculated RPN according to equation 11 are shown in Table 4.

**Table 4. calculated RPN for each risk**

| Project phases / Risk items | Initiation | Planning | Execution | Monitoring & control | Closure |
|---|---|---|---|---|---|
| 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 & 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 7:** In this step we determine the importance of risks weights in bottom levels of RBS by using mikhailov's fuzzy AHP method.

**Table 5. Risk item weight**

| **Risk item weighted** | |
|---|---|
| Product engineering | |
| Requirements | 0.08 |
| Design | 0.1 |
| Code & unit test | 0.04 |
| 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 |

**Steps 8 & 9:** calculation of final RPN according to equation 13is as below.

**Table 6. Final RPN for each risk**

| Project phases / Risk items | Initiation | Planning | Execution | Monitoring & control | Closure |
|---|---|---|---|---|---|
| $\alpha_j$ | 1 | $\frac{1}{2}$ | $\frac{1}{3}$ | $\frac{1}{4}$ | $\frac{1}{5}$ |
| 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 & 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) | (1.3,3.26.0) |
| 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 6 shows the RPN for each sub risk separately during project life cycle and Table 7 is final RPN for major risks.

**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) |

**Step 10:** as mentioned in step 10 in part 2, membership of major risk's final RPN are as below. In this step, the intersection between the major risk's final RPN and their membership function are obtained as shown in Figure 5.

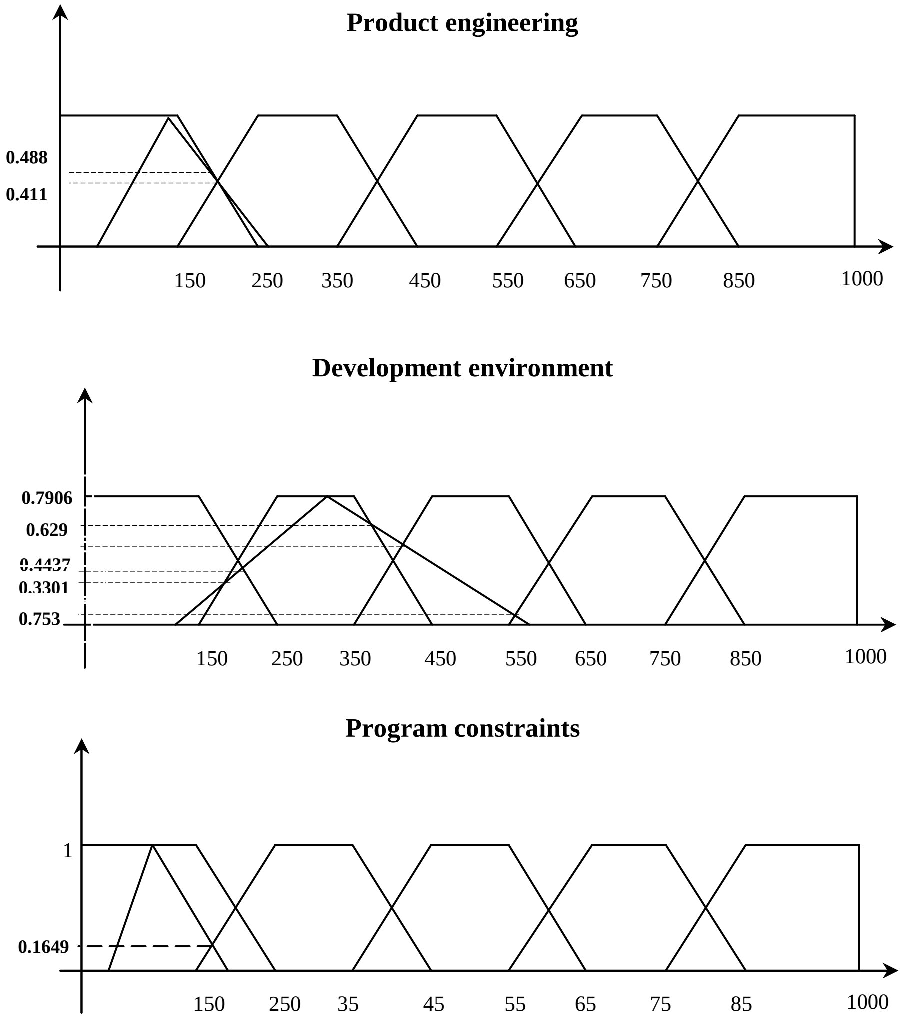


**Fig. 5. membership of major risk's final RPN**

These are the results of this intersection:

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)).

**Step 11:** as each major risk's final RPN have five linguistic variables, so the total number of rules is

$5\times5\times5=125$, 80 rules were defined in this case. There are two examples of our rules as below:

$R^1$= 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).

$R^2$= 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:** In this step, the values in Table 8 were calculated according to equations 6 and 7 and the results of step 10.

**Table 8. Fuzzy logic results**

| 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 in order to calculate the second rule which is highlighted in the Table, we have:

$$\mu_{R^2} = \mu M(development\ environment\ risk) \wedge \mu VL(program\ constraint) \wedge \mu VL(product\ engineering) = \min(0.6295,1,1) = (0.6295, \mu Mi(project\ risk\ magnitude))$$

After obtaining Table 8, the project risk magnitude can be resulted by equation 7

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

Then we should defuzzify the above result by equation 14.

$$\text{defuzzification of the Project risk magnitude}: = \frac{100\times1+400\times0.6295+700\times0.0753}{1+0.6295+0.0753} = 237.28$$

The project risk magnitude is 237.28; this is shown in the membership function below. According to figure 6, the project risk is between negligible with 31.36% and minor with 68.64%.

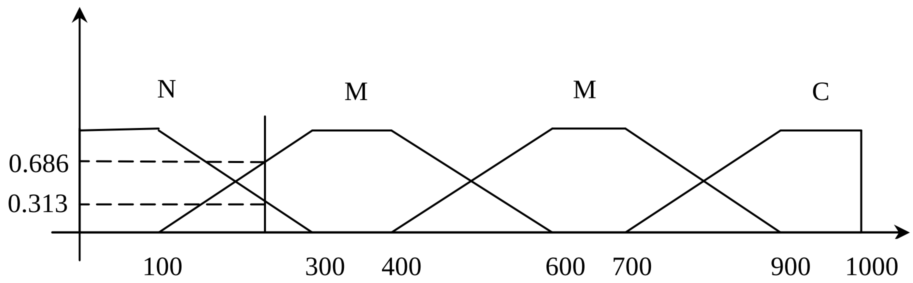


**Fig. 6. Project risk magnitude membership function**

**Step 13:** according to the project risk magnitude, as 68.64% is minor, therefore risk reduction was expected as response.

## Conclusion

In this paper, a model is presented which covers three phases of the risk management process namely, 1. Risk identification, 2. Quantitative risk analysis and 3. Risk response planning. Then, fuzzy FMEA, project life cycle weights and risk weights for determination of each major risk magnitude were aggregated. The project risk magnitude was obtained by fuzzy logic, and finally the appropriate risk response was chosen. The proposed model was applied by a numerical example and results show that considering these factors altogether in project assessment, leads to more accurate results. The quantitative models which exist to measure project risks, have not considered both fuzzy logic and FMEA concepts together. In this study, the integration of quantitative risk assessment method and fuzzy logic yielded an accurate method which provides a solution for the weakness of previous methods.

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