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Well Drilling Fuzzy Risk Assessment Using Fuzzy FMEA and Fuzzy TOPSIS

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Abstract

One of the most important issues that organizations have to deal with is the timely identification and detection of risk factors aimed at preventing incidents. Managers' and engineers' tendency towards minimizing risk factors in a service, process or design system has obliged them to analyze the reliability of such systems in order to minimize the risks and identify the probable errors. Concerning what was just mentioned, a more accurate Failure Mode and Effects Analysis (FMEA) is adopted based on fuzzy logic and fuzzy numbers. Fuzzy TOPSIS is also used to identify, rank, and prioritize error and risk factors. This paper uses FMEA as a risk identification tool. Then, Fuzzy Risk Priority Number (FRPN) is calculated and triangular fuzzy numbers are prioritized through Fuzzy TOPSIS. In order to have a better understanding toward the mentioned concepts, a case study is presented.

Keywords: Failure mode and effects analysis, Fuzzy risk priority number, Fuzzy technique for order of preference by similarity to ideal solution; Risk priority number

1 | Introduction

Failure Mode and Effects Analysis (FMEA), is a proper approach to assessing system, design, process or services. It can uncover paths, including problems, errors and risks, ending to a failure. FMEA is a preventive action with a teamwork approach. It was first developed as a design methodology in the aerospace industry to meet security and reliability requirements and then was broadly adopted in the industry field to assure the security and reliability of products [21]. It is an effective tool for predicting errors and finding the minimum cost of error-avoidance solution. FMEA is a structured technique for initializing design step or reviewing and developing product and service design in the organization. It is used to link the key parameters of an organization, related documents, design and implementation and so on [7]. Generally, FMEA avoids the

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occurrence of errors, promotes the creation and development of a great product or service and records related parameters and indices of designs and developments, process or services [1]. The output of FMEA intends to answers the following questions: what kind of errors, problems or risks are there? Which one of the identified errors, problems or risks has the highest importance (risk)? What are the remedies for reducing the occurrence probability of such cases? FMEA systematically takes the control in order to provide a correct answer to these questions. In addition to the identification of errors, problems or latent risks of a process, it prioritizes them relying on the knowledge and proficiency of a work team. Risk analysis is a part of FMEA technique applied to prevent the occurrence of a problem.

Today, organizations have discovered by experience that the concept of zero risk is no longer available and the occurrence of a problem is always probable. By improving control systems, therefore, they try to reduce the occurrence probability of problems and accidents in the work place and entrust remainder possible risks, known as residual risks in the insurance literature, to insurance companies [17]. Organizations implement FMEA for different reasons. Dale and Shaw [6] conducted a study on Ford Company. According to their results, companies implement FMEA in order to satisfy customers' needs, improve the quality and reliability of products and improve the process and safety of production [23]. FMEA is a proper methodology for engineers by which they create a structured approach in the following mental thought [21]:

- What may be done by mistake?
- What may serve as the cause of a mistake?
- What are the consequences of mistakes?

Ireson et al. believe that FMEA is an effective preventive methodology which can be easily connected to many engineering and reliability methodologies. FMEA creates an effective risk management environment through influencing the probable deficiencies of a product/service and providing planned reactions to such deficiencies [12]. According to Chrysler [6] FMEA may be described as a group of regular activities identifying and assessing the probable deficiencies of a product/service. Furthermore, it identifies those activities which can reduce or eliminate failure opportunities within a given period of time. In addition, it helps users to identify the main aspect of a design or process to be particularly controlled for production purposes and to realize those areas showing an advanced control or performance. Reviewing related literatures many studies have been carried out to strengthen FMEA using artificial intelligence, AI, modeling techniques [5]. Russomanno et al. [19] suggested in their works the application of AI systems in FMEA. Bowles and Pelaez used fuzzy logic to improve deficiency risk assessment and FMEA prioritization capability [2].

2 | Risk Priority Number

This method uses 0-10 scoring system. Every number stands for a specific level of severity, probability or detection of a problem. RPN is, indeed, the product of severity, probability and detection and depends on the following three factors [10].

$$\text{RPN} = \text{Severity} \times \text{Occurrence} \times \text{Detection}.$$

Severity (assessment and measurement of failure result) stands for the severity of a potential failure effects. It is actually a kind of assessing and measuring the consequences of a failure. The extent of severity indicates the extent of the effect of a potential failure or incident. Severity is a numerical number where the more important the effect, the higher the severity. Severity number varies from 1 to 10.

Probability (the probability of the occurrence of a failure or incidence or in other words counting the number of failures) stands for rank (value) which is used to estimate the occurrence probability of a failure or incident or, in other words, to count the number of failures. Mathematics, process capability index, reliability and probability rules can be adopted to determine the probability of each process. Probability is assessed using numerical values ranging from 1 to 10.

Detection stands for detecting an incident prior to realizing the consequences of its occurrence. RPN is assessed by a number ranging from 1 to 1000. It is used to classify required corrective actions for reducing or eliminating potential failure or incident modes. Failure/incident modes with higher RPN numbers should be assessed at the first priority. However, paying attention to the severity number of each class is of high importance. If the severity number of a class is 9 or 10, the cause should be urgently assessed regardless of the total RPN number of that class [1].

2 | Literature Review

The application of fuzzy set theory has been broadly studied due to the ambiguity of risk analysis in different engineering fields. Lee [14] adopted fuzzy set theory for comprehensive risk assessment of software development. Sadiq and Husain [20] employed a fuzzy-based method for comprehensive environmental risk assessment of drilling time loss during drilling operation. Wang and Elhag [24] used fuzzy group decision making method for bridging risk analysis purposes. In an article, Pillay and Wang [18] used fuzzy logic and FMEA grey relational analysis in navigation industry to overcome the traditional weaknesses of FMEA in risk assessment. Xu et al. [26] suggested a fuzzy FMEA estimation for engine systems in their works. Guimara and Lapa [9] adopted an absolute fuzzy logic system in the inlet water system of a reserved steam boiler of a nuclear power plant in order to improve risk ranking. Sankar and Prabhu [21] criticized RPNs due to combining P, S and D. Wang et al. [25] suggested Fuzzy Weighted Geometric Mean (FWGM), for calculating Fuzzy Risk Priority Number (FRPNs) and centroid defuzzification method for finding the centroid of fuzzy number. In an article, Bowles and Pelaez [13] used fuzzy cognitive maps to demonstrate the relationships between the causes of errors effects. They argued that fuzzy cognitive maps are an appropriate diagnosis tool in FMEA because they can demonstrate the proportions and relationships between causes and effects. This study uses a combined triangular-trapezoidal membership function. In another article, Bowles and Pelaez [2] used “if-then” logic to develop FMEA in fuzzy environment where all possible modes between severity, probability and detection parameters are studied using “if-then” logic. For instance, if severity and probability are high and detection is low, then the priority of risk will be high. This model uses a triangular-trapezoidal membership function. The study of Chang et al. [4] is another work in the field of FMEA where they introduced a relatively easy defuzzifier model to obtain the accurate value of linguistic variables. They first allocate a linguistic variable to severity, probability and detection parameters and then allocate a fuzzy number to each linguistic variable using a triangular membership function. Afterward, they defuzzify them using their defuzzifier model and calculate a relative relationship degree for each cause of the three parameters. The stronger the relationship, the weaker the effect of cause. Therefore, any increase in the relationship degree indicates improved risk priority.

4 | Methodology

In this study, selection of fuzzy membership function is done first, then fuzzy risk priority numbers calculations are done by multiplying the membership functions of Severity, Probability and Detection, finally fuzzy risk priority numbers as fuzzy numbers are prioritized using Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS).

4.1 | Explanation of a Number of Models

Fuzzy quantities are ranked based on one or more features of fuzzy numbers including the center of gravity, the area below membership function or intersection points of sets. In one ranking model, a particular property of fuzzy number is selected and variables are ranked in terms of this property. Therefore, the first rational conclusion is that we should not expect that different ranking methods assign the same ranks to the same samples of fuzzy numbers.

Methods for ranking fuzzy number are divided into two groups:

- Some methods convert a fuzzy number to a non-fuzzy number using a mapping function, F. In other words, if $\widetilde{A}$ is a fuzzy number, then F ($\widetilde{A}$) =a will be a non-fuzzy number. Then, they rank fuzzy numbers by ranking corresponding non-fuzzy numbers derived from this function. The center of gravity, the maximum membership function and left and right scores are among the techniques of this group.
- Some methods conduct a pairwise comparison on fuzzy numbers using fuzzy relations and states results with linguistic words. For example, results will be similar to this sentence: "fuzzy number $\widetilde{A}$ is better then fuzzy number $\widetilde{B}$ to some extent".

However, each method has its own advantages and disadvantages. Regarding group 1, it is argued that the conversion of a fuzzy number to a non-fuzzy number may result in the loss of a large number of data deliberately kept during calculation process. On the other hand, such methods rank considered fuzzy numbers in a stable manner. In other words, if $A^{\sim}$ is larger than $B^{\sim}$ and $B^{\sim}$ is larger than $C^{\sim}$, then $A^{\sim}$ will be always larger than $C^{\sim}$. Furthermore, there will always be a fuzzy number in ranked numbers which are introduced as the best, the second best and the third best and so on. Maintaining the linguistic words during comparison process, group 2 methods survive fuzzy information of a problem. Nevertheless, it may be impossible to determine the total rank of a fuzzy number among other fuzzy numbers using pairwise comparisons. This means that if $A^{\sim}$ is better than $B^{\sim}$ and $B^{\sim}$ is better than $C^{\sim}$, then $A^{\sim}$ might not be better than $C^{\sim}$.

The inherent complexity of techniques for ranking fuzzy numbers is not limited to this. In simple problems, the majority of techniques perform a stable ranking. Nevertheless, in more complex problems, different ranking techniques lead to different results. This means that if for some values of x, the membership functions of fuzzy numbers overlap with each other (intersect) or even if there is a slight difference between the support sets of fuzzy numbers, then different methods will most likely assign different ranks to fuzzy numbers [8].

In an article, Lavasani et al. [16] assessed offshore wells risks. The majority of offshore wells data are unknown and ambiguous data and discovering their mechanisms is a difficult and complex problem. They stated every basic risk item using a trapezoidal fuzzy number which was a combination of probability and severity.

Tay and Lim relied in their article on fuzzy inference techniques as a way for overcoming the weaknesses of classic FMEA systems. Compared with classic FMEA, fuzzy methods assess the risks of failure modes and ranks them based on expert knowledge. This article introduces a general method for modeling RPN function. Fuzzy FMEA assumes three inlet factors of RPN function, i.e., severity, probability and detection as the input factors of fuzzy RPN function. In this way, a Fuzzy Inference System (FIS) is generated along with a set of fuzzy production rules, FPRs, in order to infer input factors [15].

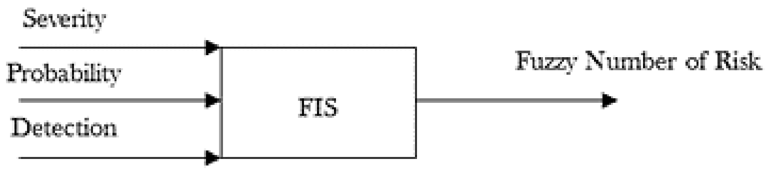

Fig. 1. FRPN model.

Ilangkumaran and Thamizhselvan identified and ranked risks in petrochemical industry. They used hazard and operability study method (HAZOP) and FMEA in order to identify and prioritize probable latent defects of a system [11].

HAZOP is an old methodology. It systematically and effectively identifies all important latent defect modes endangering human, environment, facilities and process. It was used to score FRPN which is used in FMEA. This proposed technique is used to find a better rank for defect modes. The number of risk priorities and the fuzzy adjusted geometric mean of risk are used to improve risk assessment efficiency. This makes the effective assessment of malfunctioning systems easier. The higher the fuzzy centroid value, the higher the overall risk and the higher the risk priority. All failure modes can be prioritized in terms of the fuzzified centroid values of their FRPNs [11].

In their article, Shirouyehzad et al. [22] defuzzified triangular fuzzy numbers of FRPN and then ranked them. This paper used left and right scores technique to defuzzify numbers.

4.2 | Fuzzy Risk Priority Number

After obtaining the rates of severity, probability and detection from *Tables 1*, *2* and *Table 3*, this method obtains FRPN by selecting a fuzzy membership function for each rate and forming a membership function by multiplying fuzzy membership functions.

4.2.1 | Selection of fuzzy membership function

Five linguistic variables i.e., very low (VL), low (L), moderate (M), high (H) and very high (VH) were assigned to all influential factors of risk bearing degree i.e., severity, probability and detection. These variables are assigned to the ranks as per the following *Table 1*.

Table 1. Fuzzy numbers of linguistic variables corresponding to ranks 1 to 10.

Fuzzy Number	Verbal Variable	Rank
(0.9,1,1)	VH	9,10
(0.7,0.85,1)	H	7,8,9,10
(0.4,0.6,0.8)	M	4,5,6,7,8
(0.2,0.35,0.5)	L	2,3,4,5
(0,0.15,0.3)	VL	1,2,3

{VL, L, M, H, VH} = T(x) = set of linguistic variables values,

[0, 1] = U= variation amplitude of the reference set.

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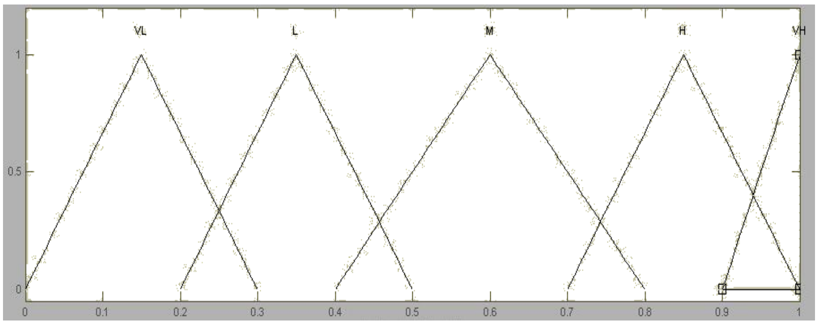

Fig. 2. Membership function of linguistic variables.

4.2.2 | Forming a membership function by multiplying the membership functions of severity, probability and detection

FRPN is calculated from the following relation by multiplying the membership functions of severity, probability and detection. If M is a linguistic variable, its triangular fuzzy number may be defined as follows:

$$M= (l, m, u).$$

Where u, l and m are the upper limit, the lower limit and the mean of u, respectively where the membership degree of l is 1.

Algebraic operations rules are applied on triangular numbers as follows to calculate RPN:

$$RPN = S \times P \times D,$$

$$FRPN = (l1, m1, u1) \times (l2, m2, u2) \times (l3, m3, u3) = (l1l2l3, m1m2m3, u1u2u3). \quad (1)$$

4.3 | Prioritization of Fuzzy Numbers Using TOPSIS

Classis TOPSIS uses accurate and precise values to determine the weight of criteria and rank options. Fuzzy TOPSIS assesses the elements of decision-making matrix or the weight of criteria, or both, using linguistic variables offered by fuzzy numbers.

This article uses Cheng and Hwang [3] technique in the case of triangular fuzzy numbers. Then, decision matrix is formed as follows:

$$\tilde{D}= \begin{bmatrix} \tilde{x}_{11} & \cdots & \tilde{x}_{1n} \\ \vdots & \ddots & \vdots \\ \tilde{x}_{m1} & \cdots & \tilde{x}_{mn} \end{bmatrix}, \quad \tilde{x}_{ij}=\left(a_{ij},b_{ij},c_{ij}\right), \quad i = (1, 2\ldots m), \quad j = (1, 2\ldots n).$$

Criteria weight matrix is defined as follows:

$$\widetilde{W} = \left[\widetilde{w}_1, \widetilde{w}_2, \widetilde{w}_3, \ldots, \widetilde{w}_n\right].$$

$$\widetilde{w}_j = \left(w_{j1}, w_{j2}, w_{j3}\right).$$

Then, fuzzy decision matrix is de-scaled:

$$\tilde{x}_{ij} = \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*}\right). \quad (2)$$

$$c_j^* = \max c_{ij}, \quad (3)$$

$$\widetilde{R} = [\tilde{r}_{ij}]_{m \times n} \quad i = 1, 2\ldots m;\ j = 1, 2, \ldots, n.$$

The fuzzy decision matrix is weighted.

$$\tilde{v}_{ij} = r_{ij}.\widetilde{w}_j, \quad (4)$$

$$\widetilde{V} = [\tilde{v}_{ij}]_{m \times n} \quad i = 1, 2\ldots m;\ j = 1, 2\ldots n.$$

Then, fuzzy ideal and non-ideal solutions are found:

$$A^* = \{\tilde{v}_1^*, \tilde{v}_2^*, \tilde{v}_3^*, \ldots, \tilde{v}_n^*\}. \quad (5)$$

$$A^- = \{\tilde{v}_1^-, \tilde{v}_2^-, \tilde{v}_3^-, \ldots, \tilde{v}_n^-\}. \quad (6)$$

$$\tilde{v}_j^* = \max \{\tilde{v}_{ij}\} \quad i = 1, 2\ldots m;\ j = 1, 2\ldots n. \quad (7)$$

$$\tilde{v}_j^- = \min \{\tilde{v}_{ij}\} \quad i = 1, 2\ldots m;\ j = 1, 2\ldots n. \quad (8)$$

The closeness to ideal and non-ideal solutions is calculated:

$$S_i^* = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_1^*),\ i = 1, 2, \ldots, m. \quad (9)$$

$$S_i^- = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_1^-),\ i = 1, 2, \ldots, m. \quad (10)$$

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$$d_v=\sqrt{\frac{1}{3}[(a_1-a_2)^2+(b_1-b_2)^2+(c_1-c_2)^2}. \quad (12)$$

Finally, similarity index is calculated and alternatives are ranked:

$$CC_i=\frac{S_i^-}{S_i^*+S_i^-}\ i=1,2,\ldots,m. \quad (12)$$

5 | Case Study

The following case study was conducted on gas and oil wells drilling operations using FRPN techniques. According to the following table, there are 8 potential failure modes each has different effects, causes and detection probabilities determined by FMEA team. Severity, probability and detection numbers are defined using related tables and by the aid of FMEA team. The RPN of all 8 potential failure modes is determined. The last column of *Table 2* shows the control actions required for each mode.

After determining corresponding linguistic variables for the values, the fuzzy numbers of severity, probability and detection is defined using membership function and in accordance with *Table 1*. Then, FRPN is calculated as per *Table 4*. Finally, fuzzy TOPSIS is used to prioritize them.

Table 2. Formation of fuzzy membership function for severity, probability, and detection for all 8 potential failure modes.

#	Severity	Probability	Detection
1	(0.4,0.6,0.8)	(0.9,1,1)	(0,0.15,0.3)
2	(0.7,0.85,1)	(0,0.15,0.3)	(0.2,0.35,0.5)
3	(0.4,0.6,0.8)	(0.2,0.35,0.5)	(0.4,0.6,0.8)
4	(0.7,0.85,1)	(0.4,0.6,0.8)	(0.2,0.35,0.5)
5	(0.4,0.6,0.8)	(0.4,0.6,0.8)	(0,0.15,0.3)
6	(0.4,0.6,0.8)	(0.4,0.6,0.8)	(0,0.15,0.3)
7	(0.7,0.85,1)	(0.7,0.85,1)	(0,0.15,0.3)
8	(0.7,0.85,1)	(0.7,0.85,1)	(0,0.15,0.3)

After determining the linguistic variables of severity, probability and detection for all 8 potential failure modes, fuzzy values are substituted as per *Table 3*. Then, FRPNs are calculated using *Eq. (1)* and in accordance with *Table 4*.

Now, all 8 potential failure modes are prioritized using fuzzy TOPSIS. Criteria are considered positive values and each member is divided into the maximum number of each column as per *Eq. (2)* in order to normalize and de-scale them. Then, they are multiplied by the weight matrix as per *Eq. (4)*. Since there is the same number of criteria, the balanced matrix will be similar to the previous matrix. *Table 5* shows obtained values.

$$\tilde{R}=\tilde{V}.$$

Table 3. FMEA table.

#	Process Function	Potential Failure Mode	Potential Effect(s) of Failure	Severity	Potential Cause(s)/ Mechanism(s) of Failure	Probability	Current Process Controls	Detection	RPN
1	Check top drive & run in hole	Collapse/part of 9-5/8" casing	Technical non-productive time (NPT) for contractor.	5	Poor cementing / poor design of casing.	9	Pressure test of annulus both positive& negative run in hole with bit.	1	45
2	Drilling 6-1/8" hole section	Low progress	More time than program.	8	Deviated hole& abnormal parameters.	1	Monitoring surface parameters& optimization.	3	24
3	Side track the well	Low progress in side tracking	More time than program.	6	Utilizing heavy duty material in 4-3/4" positive displacement motors hardness of formation& low motor efficiency.	3	Calculate time more than the previous drilling operation.	4	72
4	5" liner lap leakage	Leakage in liner lap	More time than program.	7	Poor cementing of liner.	5	Abnormal surface pressure.	2	70
5	Fish in hole	Fish in hole while drilling cement plugs	More cost for contractor due to remedial actions.	5	Hard cement & harsh parameters.	4	Drill out cement to evaluate quality.	1	20
6	Opening window	More time in opening window & rupture of tri mill	More time than program.	5	Low quality of tri mill strength of casing due to high thickness.	4	Casing coupling log (CCL) & segmented bond tool (SBT) log.	1	20
7	Flowing the well	Well does not flow normally	Excess operations & cost.	7	Formation damage& skin.	7	Poor wellhead pressure after perforation.	1	49
8	Running 7" liner	Liner stuck	More time than program.	8	Poor hole condition& dog leg severity.	7	Monitoring of condition trips determining tight holes.	1	56

Table 4. Formation of membership function by multiplying the membership functions of severity, probability and detection.

#	FRPN
1	(0,0.09,0.24)
2	(0,0.0446,0.15)
3	(0.032,0.126,0.32)
4	(0.056,0.1785,0.4)
5	(0,0.054,0.192)
6	(0,0.054,0.192)
7	(0,0.108,0.3)
8	(0,0.108,0.3)

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Table 5. Formation of membership function by multiplying the membership functions of severity, probability and detection.

#	FRPN ($\tilde{V}$)
1	(0,0.5042,0.6)
2	(0,0.2499,0.375)
3	(0.5714,0.7059,0.8)
4	(1,1,1)
5	(0,0.3025,0.48)
6	(0,0.3025,0.48)
7	(0,0.6067,0.75)
8	(0,0.6067,0.75)
$\tilde{v}^*$	(1,1,1)
$\tilde{v}^-$	(0,0,0)

At this point, the closeness to ideal and non-ideal solutions and similarity index are calculated in accordance with relations 11, 10, 9, 12.

Table 6. Calculating closeness to ideal and non-ideal solutions and similarity index.

#	CC_i	S_i^-	S_i^*
1	0.34	0.4525	0.8918
2	0.21	0.2602	0.9656
3	0.49	0.6988	0.7154
4	1	1	0
5	0.26	0.3276	0.9448
6	0.26	0.3276	0.9448
7	0.4	0.5570	0.8305
8	0.4	0.5570	0.8305

The priority of activities is obtained as follows:

Activity 4, activity 3, activities 7 and 8, activity 1, activities 5 and 6, activity 2.

The comparison of the obtained results with those of non-fuzzy RPN technique demonstrates ranking difference.

Result Of non-fuzzy RPN Ranking were:

Activity 3, activity 4, activity 8, activity 7, activity 1, activities 2, activities 5 and 6.

6 | Conclusion

Given the importance of recognizing risk factors and their multiplicity, it is important to prioritize them. This article first identified hazards using FMEA tool and conducting teamwork for each activity. Second, it examined the relative priority of these factors with the help of the RPN, the FRPN, and TOPSIS. Extensive research has been done for improving the FMEA methodology using such techniques as fuzzy logic. This article tried to maintain the fuzzy information of problem by maintaining fuzzy logic values equivalent to linguistic terms in comparison process. In simple problems, most methods perform ranking, but in more complex problems, they lead to different results. In other words, for some X values, if fuzzy number membership functions overlap (intersect) with each other or even if fuzzy number support sets slightly differ with each other, various methods will most likely assign different rankings to fuzzy numbers.

The fuzzy number ranking results presented in this article can be challenged through comparing them with the results of the Fuzzy Techniques for Order of Preference by Similarity to Ideal Solution (FTOPSIS) method. The same method can also be used for calculating the fuzzy risk level in qualitative and

semi-quantitative risk assessment techniques with two and more than two dimensions.

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