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Risk evaluation using a novel hybrid method based on FMEA, extended MULTIMOORA, and AHP methods under fuzzy environment

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A B S T R A C T

Failure mode and effects analysis (FMEA) is one of the most important risk assessment tools which has been extensively used in different industries and organizations. In the conventional FMEA, sometimes the difference between some failure modes cannot be distinguished. In order to evaluate various failure modes more precisely, a novel fuzzy hybrid model for FMEA is proposed in this paper. In this method, fuzzy weighted risk priority number (FWRPN) is considered instead of RPN for each failure. The weights of the three factors and the weights of failure modes are computed by extended fuzzy AHP and fuzzy MULTIMOORA methods, respectively. The proposed fuzzy MULTIMOORA method calculates the weight of each failure based on three criteria of time, cost, and profit through fuzzy linguistic terms. After calculating FWRPN for each failure, corrective actions are performed for eliminating the identified failures or decreasing the effects of them. Then, corrected fuzzy weighted risk priority number (CFWRPN) is computed for each failure. Finally, the average of FWRPNs (AFWRPNs) with the average of CFWRPNs (ACFWRPNs) are compared to evaluate the effectiveness of corrective actions by a novel ranking fuzzy numbers method. In addition, the proposed ranking fuzzy number method is also used in both previously mentioned fuzzy multi-criteria decision making (MCDM) methods. Eventually, Kerman Steel Industries Factory is considered as a case study to demonstrate the applicability and benefits of the proposed fuzzy hybrid method. A sensitivity analysis is performed to validate the obtained results. Findings show that AFWRPNs decreased by 56% compared to ACFWRPNs.

1. Introduction

Risk evaluation is a logical method to determine quantitative and qualitative value of risks and investigate potential consequences of probable accidents on people, materials, products, equipment, and environment. Nowadays, application of risk evaluation methods in different industries and organizations is growing. One of the most important of these methods is failure mode and effects analysis (FMEA). FMEA is an analytical method in risk assessment which tries as much as possible to identify and prioritize potential risks in areas where risk assessment is done and also to determine and score causes and effects which are associated with them. In other words, it is a strong and helpful tool which can be employed to define, identify, and eliminate known and/or potential failures, problems, errors, and so on from the system, design, process, and/or service before they reach customers (Stamatis, 2003; Kutlu and Ekmekçioğlu, 2012; Cicek and Celik, 2013).

The United States Army performed and developed the FMEA technique for the first time in 1949. Afterwards, in the 1970s, because of its capability and effectiveness, it was first used in aerospace and automotive industry, then in general manufacturing (Scipioni et al., 2002). The purpose of the FMEA is to improve the system reliability. To achieve this goal, first it should be employed to identify and prioritize potential failure modes in order to assign the limited resources to the most essential ones of them. Then, some necessary preventive and corrective actions should be considered to eliminate the identified failure modes or to decrease the effects of them (Liu et al., 2014a). Nowadays, many engineers widely apply the FMEA methodology to ensure the safety and reliability of people, products, materials, equipment, and processes in various industries (Chang et al., 2012; Kutlu and Ekmekçioğlu, 2012; Song et al., 2014; Vinodh et al., 2012).

In the conventional FMEA, ranking of each failure mode is determined by risk priority number (RPN) which is calculated by multiplying the values of three risk factors: occurrence (O), severity (S), and detection (D). That is:

$$RPN = O \times S \times D \tag{1}$$

where O is the occurrence probability of a failure, S is the severity of a failure, and D is the detection probability of a failure before its effects are realized. Each of three factors can take a number between 1, the

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best case, and 10, the worst case. To implement the corrective actions on failure modes, due to the higher risk associated with the corresponding failure mode, the ones with higher RPNs would be prior to others. After the implementation of the corrective actions, the RPNs should be recalculated to investigate the effectiveness of the performed corrective actions.

The RPNs with crisp values in conventional FMEA have been widely criticized in the previous studies for different reasons (Ben-Daya and Raouf, 1996; Bowles, 2003; Chin et al., 2009b; Gargama and Chaturvedi, 2011; Kutlu and Ekmekçioğlu, 2012; Liu et al., 2013; Seyed-Hosseini et al., 2006; Wang et al., 2009a). A number of studies in the literature presented various solutions to overcome the weaknesses of the conventional FMEA (Song et al., 2014; Liu et al., 2011, 2012; Chin et al., 2009a, 2009b; Seyed-Hosseini et al., 2006). The fuzzy approach is one of the ways to resolve some shortcomings of the conventional RPN (Wang et al., 2009a). Zadeh (1965) presented the fuzzy set theory for the first time. In the fuzzy FMEA, experts describe the three risk factors O, S, and D through the fuzzy linguistic terms. The studies in the fuzzy FMEA literature have mostly considered fuzzy if-then rule based approach, where conditional parts and/or conclusions include linguistic variables (Bowles and Peláez, 1995; Jong et al., 2013; Kahraman et al., 2013; Pillay and Wang, 2003; Sharma et al., 2005; Vinodh et al., 2012). Yang and Wang (2015) proposed a new method to overcome the weaknesses of the conventional fuzzy rule-based methods in FMEA. They combined the method with fuzzy evidential reasoning (FER) approach to model the safety of offshore engineering systems. Wang et al. (2009a) considered the risk factors O, S, and D as fuzzy variables instead of using fuzzy if-then rules. Tooranloo and Sadat Ayatollah (2016) presented a novel model of FMEA based on an intuitionistic fuzzy approach to evaluate the failure criteria for quality of internet banking services.

There are many quantitative and qualitative risk evaluation tools in the literature. Multi-criteria decision making (MCDM) is one of the most important tools. MCDM is a method that explicates the decision maker's preferences in multiple criteria environments (Gul and Guneri, 2016). The analytic hierarchy process (AHP) approach is one of the most widely used MCDM methods. Saaty (1980) proposed the AHP technique for the first time. The classical AHP considers the explicit judgments of decision makers (Wang and Chen, 2007). Fuzzy MCDM methods are utilized to model the vagueness of many systems in real world which comprise incomplete and imprecise information (Karsak and Dursun, 2015). In fuzzy MCDM methods, the relative importance of criteria is determined by decision makers using fuzzy numbers instead of crisp numbers. In the literature, various methods have been suggested for the fuzzification of AHP. Van Laarhoven and Pedrycz (1983) firstly fuzzified AHP.

Gul et al. (2017b) introduced a hybrid risk-based method for maritime industry using MCDM methods to reduce risks which may cause dangerous accidents in maritime transportations. They utilized fuzzy AHP with fuzzy VIKOR (the VlseKriterijumska Optimizacija I Kompromisno Resenje) methods under Fine-Kinney approach. Gul and Guneri (2016) proposed a fuzzy multi criteria risk assessment based on "the decision matrix technique" for an aluminum plate manufacturing factory. They scored two risk factors likelihood and severity related to the hazards using fuzzy AHP (FAHP) method. After that, 23 various hazard groups were prioritized using fuzzy TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) approach. Gul et al. (2017a) suggested a two-stage fuzzy multi-criteria approach including fuzzy AHP (FAHP) and fuzzy VIKOR (FVIKOR) methods to evaluate risks in a Turkish hospital. They scored five risk parameters by using FAHP approach and then prioritized hazard types in each sector of the hospital using FVIKOR method.

Considering that different failure modes should be prioritized and ranked in the FMEA approach, it can be typically considered as a group MCDM problem. Accordingly, MCDM methods can be applied to the FMEA approach. The AHP method has been used on the basis of the FMEA approach in previous studies. Hu et al. (2009) applied both FMEA and FAHP methods to identify risk evaluation criteria. In their method, FAHP approach was considered to determine the relative weights of the risk factors in order to evaluate the risks of green components. A new fuzzy FMEA approach with linguistic variables for the three risk factors through fuzzy TOPSIS integrated with fuzzy AHP was presented by Kutlu and Ekmekçioğlu (2012). Liu et al. (2015b) suggested a new approach for FMEA based on fuzzy AHP, entropy, and fuzzy VIKOR methods. In the method, integration of FAHP and entropy methods was utilized for risk factor weighting.

In the work of Ozdemir et al. (2017), a novel risk evaluation methodology including 5S approach, FMEA, interval type-two fuzzy sets (IT2FSs), AHP, and VIKOR was suggested for a university chemical laboratory. They incorporated AHP into IT2FSs in the assessment step of three parameters of FMEA: S, O, and D. Sutrisno et al. (2015) developed and applied a modified FMEA approach to access the criticality of waste in maintenance operations. They utilized the AHP method to obtain the weight of the maintenance waste category. In a study, Omidvar and Nirumand (2017) explored the development of an extension of FMEA approach. In the method, they used the fuzzy VIKOR approach to prioritize the failure modes and applied the fuzzy AHP method to obtain the weight of the risk factors in geothermal power plant (GPP) as a case study. In addition, the concepts of Z number and Shannon entropy were also utilized in their approach.

The multi-objective optimization by ratio analysis (MOORA) method is another MCDM approach that was presented by Brauers and Zavadskas (2006). This method includes two parts, namely the ratio system and the reference point approach. The MOORA method was developed by Brauers and Zavadskas (2010) which considered the full multiplicative form. This extended technique was named the multiple multi-objective optimization by ratio analysis (MULTIMOORA). In other words, three aspects including the ratio system, the reference point, and the full multiplicative form are incorporated in the MULTIMOORA method. Consequently, the MULTIMOORA method has been the most robust approach for multiple objectives optimization up to now (Brauers and Zavadskas, 2012). Many researchers investigated MULTIMOORA method and its extensions. Brauers et al. (2011) updated the MULTIMOORA method with the theory of triangular fuzzy number. The MULTIMOORA method was developed with generalized interval-valued trapezoidal fuzzy numbers by Baležentis and Zeng (2013). In the work of Liu et al. (2014b), an improved MULTIMOORA method was combined with the interval 2-tuple linguistic mode to solve health-care waste (HCW) treatment technology selection problem under uncertainty.

Liu et al. (2015a) presented a new hybrid MCDM model by combining the fuzzy MULTIMOORA approach and the 2-tuple decision-making trial and evaluation laboratory (DEMATEL) technique to select the best treatment technology in the HCW management system. Hafezalkotob and Hafezalkotob (2015) developed the MULTIMOORA approach utilizing target-based attributes for materials selection in biomedical applications. A developed MULTIMOORA method under an internal environment based on fuzzy logic theory and a new preference technique was introduced by Hafezalkotob et al. (2016) to solve a real-world decision making problem regarding materials selection of power gears. Souzangarzadeh et al. (2017) applied a combination of extended MULTIMOORA and numeric logic (NL) methods to acquire the optimum design for a conical segmented aluminum tube. In the work of Gou et al. (2017), a double hierarchy hesitant fuzzy linguistic MULTIMOORA (DHHFL-MULTIMOORA) method was proposed to solve a practical MCDM problem. A comprehensive survey on applications of the MULTIMOORA method and its extensions was also presented by Baležentis and Baležentis (2014).

In the literature, there are a few studies in which the MULTIMOORA method has been either used as a risk evaluation tool or applied to the FMEA approach. Stankevičienė and Sviderskė (2012) proposed a risk evaluation model based on the MULTIMOORA method to assess country risk in Baltic States by considering various factors which affect economic and socio-political environment of countries. In the work of Liu et al. (2014a), a novel risk priority model was introduced for assessing the risk of failure modes in FMEA method based on extended MULTIMOORA approach under fuzzy environment. In other words, they applied the MULTIMOORA approach to FMEA method in order to determine the risk priority order of identified failure modes. Zhao et al. (2016) suggested a new method for FMEA based on MULTIMOORA approach and interval-valued intuitionistic fuzzy sets (IVIFSs). In the method, the MULTIMOORA approach was applied with continuous weighted entropy to determine risk priority of failure modes under interval-valued intuitionistic fuzzy (IVIF) environment. Furthermore, Liu et al. (2013) implemented a comprehensive review of the risk evaluation approaches in FMEA.

In the above-mentioned papers, the weights of the three factors and the weights of each failure mode were not considered simultaneously and there are a few studies in which the MULTIMOORA method has been applied to the FMEA approach. For these reasons, a novel fuzzy hybrid method based on fuzzy FMEA, extended fuzzy MULTIMOORA, and fuzzy AHP methods are proposed in this paper in which the weights of the three factors and the weight of each failure mode are computed by the extended fuzzy AHP and fuzzy MULTIMOORA methods, respectively. This resulted in more precise computation of RPNs as well as the improved the effectiveness of the FMEA method. Furthermore, in the proposed fuzzy MULTIMOORA method unlike the traditional method, the weight of each alternative is also calculated. In this study, the criteria utilized by MULTIMOORA are time, cost, and profit which are defined as follows: the required time to perform the proposed corrective actions for decreasing or eliminating the effects of failure, the required cost to conduct the proposed corrective actions for decreasing or eliminating the effects of failure, and the profit obtained from decreasing or eliminating the effects of failure. In addition, a novel method for ranking fuzzy numbers is also used in both previously mentioned fuzzy MCDM methods.

The structure of this paper is as follows. Section 2 introduces the fuzzy set theory and a novel ranking fuzzy numbers method, whereas, Section 3 depicts the proposes fuzzy MCDM methods and Section 4 presents the proposed fuzzy hybrid model for FMEA. Subsequently, Section 5 elaborates on the application of the proposed method for Kerman Steel Industries Factory and demonstrates its results. Finally, some conclusions and future remarks are drawn in Section 6.

2. Fuzzy set theory and a novel method for ranking fuzzy numbers

2.1. Fuzzy set theory

A fuzzy set is characterized by a membership function. The most common uses of fuzzy numbers are triangular and trapezoidal fuzzy numbers. In this paper, fuzzy numbers are considered as triangular fuzzy numbers. Fig. 1 shows a typical triangular fuzzy number in which three numbers are required to be demonstrated as (a,b,c).

The membership function of triangular fuzzy numbers is as follows

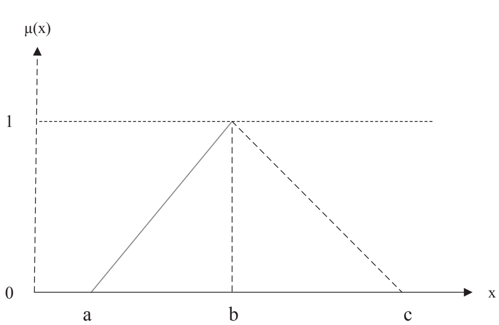

Fig. 1. Triangular fuzzy number.

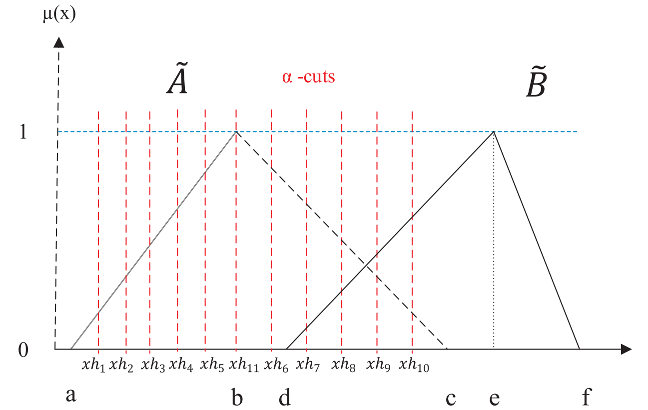

Fig. 2. Comparing two triangular fuzzy numbers with no vertical sides ($a \neq b \neq c$).

(Wang et al., 2009a):

$$\mu_{\widetilde{A}}(x) = \begin{cases} \frac{x-a}{b-a}; & a \leqslant x \leqslant b \\ \frac{c-x}{c-b}; & b \leqslant x \leqslant c \\ 0; & otherwise \end{cases} \tag{2}$$

The basic operations of any two positive triangular fuzzy numbers $\widetilde{A} = (a,b,c)$ and $\widetilde{B} = (d,e,f)$ and a positive real number r, can be expressed as follows (Liu et al., 2014a):

$$\widetilde{A} \oplus \widetilde{B} = [a+d, b+e, c+f] \tag{3}$$

$$\widetilde{A} \ominus \widetilde{B} = [a-f, b-e, c-d] \tag{4}$$

$$\widetilde{A} \otimes \widetilde{B} \cong [ad, be, cf] \tag{5}$$

$$\widetilde{A} \otimes \mathrm{r} = [ar, br, cr] \tag{6}$$

2.2. A novel method for ranking fuzzy numbers

The two triangular fuzzy numbers, $\widetilde{A} = (a,b,c)$ and $\widetilde{B} = (d,e,f)$ shown in Fig. 2, are compared by their equivalent crisp numbers. The important question is how to save the characteristics of a fuzzy number while changing it into a crisp number. In the following, a novel method is presented.

In this method, three possible modes are considered for a triangular fuzzy number:

(1) Triangular with no vertical sides ($a \neq b \neq c$) (Fig. 2):

First, five vertical $\alpha-cuts$ with equal distances are drawn between a and b.

$$xh_i = a + i\left(\frac{b-a}{6}\right), \quad i = 1,2,3,4,5 \tag{7}$$

Second, the places of each $\alpha-cut$ to deal with the side ab are calculated.

$$yh_i = \left(\frac{1}{b-a}\right)*(xh_i-a), \quad i = 1,2,3,4,5 \tag{8}$$

It is also performed for side bc.

$$xh_i = a + i\left(\frac{c-b}{6}\right), \quad i = 6,7,8,9,10 \tag{9}$$

$$yh_i = \left(\frac{-1}{c-b}\right)*(xh_i-b) + 1, \quad i = 6,7,8,9,10 \tag{10}$$

And also, $xh_{11} = b$ and $yh_{11} = 1$ are assumed. Finally, the equivalent crisp number of the triangular fuzzy number $\widetilde{A}$ is calculated as follows:

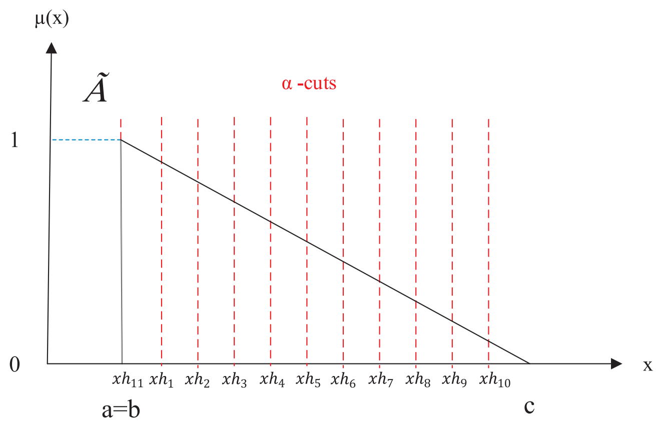

Fig. 3. Triangular fuzzy number with a vertical side ($a = b, b < c$).

$$R_{\tilde{A}} = \sum_{i=1}^{10} (xh_i * yh_i^{0.01}) + b \quad (11)$$

(2) Triangular with a vertical side ($a = b, b < c$) (Fig. 3):

First, ten vertical $\alpha-cuts$ with equal distances are drawn between a and c.

$$xh_i = a + i\left(\frac{c-a}{11}\right), \quad i = 1,2,3,...,10 \quad (12)$$

Second, the places of each $\alpha-cut$ to deal with the side bc are calculated.

$$yh_i = \left(\frac{-1}{c-b}\right) * (xh_i - b) + 1, \quad i = 1,2,3,...,10 \quad (13)$$

And also, $xh_{11} = a$ and $yh_{11} = 1$ are assumed. Finally, the equivalent crisp number of the triangular fuzzy number $\tilde{A}$ is calculated as follows:

$$R_{\tilde{A}} = \sum_{i=1}^{10} (xh_i * yh_i^{0.01}) + a \quad (14)$$

(3) Triangular with a vertical side ($b = c, a < b$) (Fig. 4):

First, ten vertical $\alpha-cuts$ with equal distances are drawn between a and c.

$$xh_i = a + i\left(\frac{c-a}{11}\right), \quad i = 1,2,3,...,10 \quad (15)$$

Second, the places of each $\alpha-cut$ to deal with the side bc are calculated.

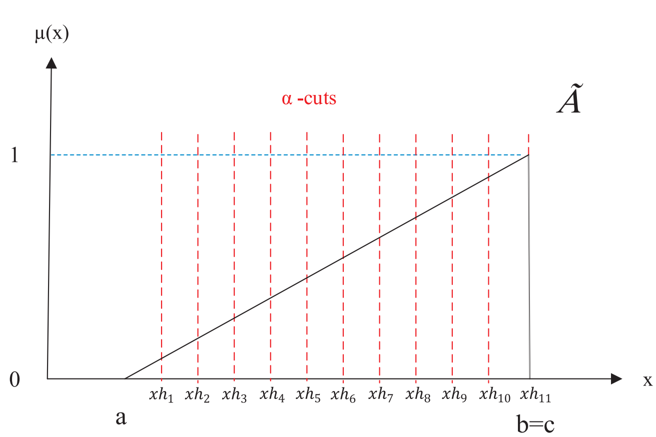

Fig. 4. Triangular fuzzy number with a vertical side ($b = c, a < b$).

$$yh_i = \left(\frac{1}{b-a}\right) * (xh_i - a), \quad i = 1,2,3,...,10 \quad (16)$$

And also, $xh_{11} = b$ and $yh_{11} = 1$ are assumed. Finally, the equivalent crisp number of the triangular fuzzy number $\tilde{A}$ is calculated as follows:

$$R_{\tilde{A}} = \sum_{i=1}^{10} (xh_i * yh_i^{0.01}) + b \quad (17)$$

By the same method as the one described above, the equivalent crisp number of the triangular fuzzy number $\tilde{B}$ is also calculated as $R_{\tilde{B}}$. In the end, the ratio of the crisp numbers $R_{\tilde{A}}$ and $R_{\tilde{B}}$ is considered as the ratio of two fuzzy numbers $\tilde{A}$ and $\tilde{B}$. It should be mentioned that although ten $\alpha-cuts$ were conducted in this method, the use of more $\alpha-cuts$ will result in higher accuracy regarding the calculation of the equivalent crisp amount of a fuzzy number. Moreover, both vertical and horizontal dimensions of a fuzzy number should be used together. However, the horizontal dimension intensity must exceed the vertical one. This is the main reason for the power 0.01 of yh_i, when calculating the $R_{\tilde{A}}$ or $R_{\tilde{B}}$. The power 0.01 is a result of many trial and error calculations which have led to the highest accuracy. To show the effectiveness and validation of the proposed ranking fuzzy numbers method, a comparative example will be provided in the following.

2.2.1. Comparative example

In this example, eight ranking fuzzy numbers methods introduced by different scholars are compared with the proposed ranking fuzzy numbers method. These methods are as follows:

(1) Wang et al. (2009b), (2) Abbasbandy and Hajjari (2009), (3) Abbasbandy and Hajjari (2009), (4) Cheng (1998), (5) Chu and Tsao (2002), (6) Deng et al. (2006), (7) Cheng (1998), and (8) Nejad and Mashinchi (2011). In the example, the triangular fuzzy numbers of sets 1, 2, 3, 4, and 5 are compared with each other separately by the eight mentioned methods and the proposed novel method. The results are illustrated in Table 1. Sets 1 to 5 are as follows:

Set 1: $\tilde{A} = (1,1,3)$, $\tilde{B} = (1,1,7)$
Set 2: $\tilde{A} = (2,4,6)$, $\tilde{B} = (1,5,6)$, $\tilde{C} = (3,5,6)$
Set 3: $\tilde{A} = (2,3,8)$, $\tilde{B} = (2,3,10)$
Set 4: $\tilde{A} = (1,5,5)$, $\tilde{B} = (2,3,5)$
Set 5: $\tilde{A} = (2,4,6)$, $\tilde{B} = (1,5,6)$

As evident from the results, the proposed method with a procedure much simpler than the previous methods, properly performs the comparison of the proposed sets.

Table 1
Results of ranking sets by mentioned methods and proposed method.

Method	Set 1	Set 2	Set 3	Set 4	Set 5
1	$\tilde{A} \sim \tilde{B}$	$\tilde{A} \sim \tilde{B} < \tilde{C}$	$\tilde{A} < \tilde{B}$	$\tilde{A} < \tilde{B}$	$\tilde{B} < \tilde{A}$
2	$\tilde{A} < \tilde{B}$	$\tilde{A} < \tilde{B} < \tilde{C}$	$\tilde{A} < \tilde{B}$	$\tilde{B} < \tilde{A}$	$\tilde{A} < \tilde{B}$
3	$\tilde{A} < \tilde{B}$	$\tilde{A} < \tilde{B} < \tilde{C}$	$\tilde{A} < \tilde{B}$	$\tilde{B} < \tilde{A}$	$\tilde{A} < \tilde{B}$
4	$\tilde{A} < \tilde{B}$	$\tilde{A} < \tilde{B} < \tilde{C}$	$\tilde{A} < \tilde{B}$	$\tilde{A} < \tilde{B}$	$\tilde{A} < \tilde{B}$
5	$\tilde{A} < \tilde{B}$	$\tilde{A} < \tilde{B} < \tilde{C}$	$\tilde{A} < \tilde{B}$	$\tilde{B} < \tilde{A}$	$\tilde{A} < \tilde{B}$
6	$\tilde{A} < \tilde{B}$	$\tilde{A} < \tilde{B} < \tilde{C}$	$\tilde{A} < \tilde{B}$	$\tilde{A} < \tilde{B}$	$\tilde{A} < \tilde{B}$
7	$\tilde{B} < \tilde{A}$	$\tilde{B} < \tilde{A} < \tilde{C}$	$\tilde{B} < \tilde{A}$	$\tilde{A} < \tilde{B}$	$\tilde{B} < \tilde{A}$
8	$\tilde{A} < \tilde{B}$	$\tilde{A} < \tilde{B} < \tilde{C}$	$\tilde{A} \sim \tilde{B}$	$\tilde{B} < \tilde{A}$	$\tilde{A} < \tilde{B}$
Proposed method	$\tilde{A} < \tilde{B}$	$\tilde{A} < \tilde{B} < \tilde{C}$	$\tilde{A} < \tilde{B}$	$\tilde{B} < \tilde{A}$	$\tilde{A} < \tilde{B}$

Table 2
Fuzzy evaluation scores.

Linguistic variable	Crisp Number	Triangular fuzzy number	Reciprocal triangular fuzzy number
Equal	1	(1, 1, 1)	(1, 1, 1)
Moderate	3	(1, 1, 1.5)	(2/3, 1, 1)
Strong	5	(1, 1.5, 2)	(1/2, 2/3, 1)
Very strong	7	(1.5, 2, 2.5)	(2/5, 1/2, 2/3)
Extreme	9	(2, 2.5, 3)	(1/3, 2/5, 1/2)

Table 3
Linguistic variables for rating the alternatives (Liu et al., 2015a).

Linguistic variable	Triangular fuzzy number
Very low (VL)	(0, 0, 1)
Low (L)	(1, 2, 3)
Medium low (ML)	(1, 3, 5)
Medium (M)	(3, 5, 7)
Medium high (MH)	(5, 7, 9)
High (H)	(7, 9, 10)
Very high (VH)	(9, 10, 10)

Table 4
Occurrence rating scale (Silva et al., 2014).

Rating	Description	Potential failure rate
10	Certain probability of occurrence	Failure occurs at least once a day, or failure occurs almost every time
9	Failure is almost inevitable	Failure occurs predictably, or failure occurs every 3–4 days
8	Very high probability of occurrence	Failure occurs frequently, or failure occurs about once per week
7		
6	Moderately high probability of occurrence	Failure occurs approximately once per month
5		
4	Moderate probability of occurrence	Failure occurs occasionally, or failure occurs once every 3 months
3		
2	Low probability of occurrence	Failure occurs rarely, or failure occurs about once per year
1	Remote probability of occurrence	Failure almost never occurs; no one remembers the last failure

3. The proposed novel fuzzy multi-criteria decision making (MCDM) methods

3.1. The new fuzzy AHP method

The steps of the proposed new fuzzy AHP method are as follows:

Step 1. Hierarchical structure of AHP method is determined for the problem.
Step 2. Fuzzy pair-wise comparison matrix for criteria with regard to the objective is formed by experts, considering Table 2.
Step 3. The fuzzy numbers of each column are summed by using Eq. (3).
Step 4. Ratio of each fuzzy number with the obtained summed value for each column in **step 3**, is calculated by the proposed ranking fuzzy numbers method.
Step 5. Weight of each criterion is obtained by the arithmetic mean of the numbers in each row.

3.2. The extended fuzzy MULTIMOORA method

The difference between this proposed fuzzy MULTIMOORA method and the conventional method is that unlike the traditional one, it can calculate the weight of each alternative in the three approaches and then their final weights.

The steps of the extended fuzzy MULTIMOORA method are as follows:

Step 1. Aggregate the decision makers' opinions

The aggregated fuzzy ratings $\widetilde{x}_{ij}^k = (x_{ij1}^k, x_{ij2}^k, x_{ij3}^k)$ of alternatives regarding each criterion can be measured to construct a fuzzy group decision matrix $\widetilde{X} = [\widetilde{x}_{ij}]_{m\times n}$ using Eqs. (18) and (19) (Liu et al., 2015a):

$$\widetilde{x}_{ij} = (x_{ij1}, x_{ij2}, x_{ij3}) \tag{18}$$

$$x_{ij1} = \frac{1}{l}\sum_{k=1}^{l} x_{ij1}^k,\quad x_{ij2} = \frac{1}{l}\sum_{k=1}^{l} x_{ij2}^k,\quad x_{ij3} = \frac{1}{l}\sum_{k=1}^{l} x_{ij3}^k \tag{19}$$

It should be noted that the decision makers calculated fuzzy ratings $\widetilde{x}_{ij}^k = (x_{ij1}^k, x_{ij2}^k, x_{ij3}^k)$ of alternatives for each criterion through Table 3.

Step 2. Normalize the fuzzy group decision matrix

The fuzzy group decision matrix $\widetilde{X}$ can be transformed into a normalized fuzzy decision matrix $\widetilde{R} = [\widetilde{r}_{ij}]_{m\times n}$ through the vector normalization method (Liu et al., 2015a):

$$\widetilde{r}_{ij} = (r_{ij1}, r_{ij2}, r_{ij3}) = \left(\frac{x_{ij1}}{x_{ij3}^*}, \frac{x_{ij2}}{x_{ij3}^*}, \frac{x_{ij3}}{x_{ij3}^*}\right) \tag{20}$$

$$x_{ij3}^* = \sqrt{\sum_{i=1}^{m} x_{ij3}^2} \tag{21}$$

Step 3. Calculate the weights of each criterion

In the proposed method, the weight of each criterion is obtained by the proposed AHP method stated before.

Table 5
Severity rating scale (Silva et al., 2014).

Rating	Description	Definition
10	Extremely dangerous	Failure could cause the death of a customer (patient, visitor, employee, staff member, business partner) and/or total system breakdown, without any prior warning
9	Very dangerous	Failure could cause a major or permanent injury and/or serious system disruption with interruption in service, with prior warning
8		
7	Dangerous	Failure could cause a minor to moderate injury with a high degree of customer dissatisfaction and/or major system problems requiring major repairs or significant re-work
6		
5	Moderate danger	Failure could cause a minor injury with some customer dissatisfaction and/or major system problems
4	Low to moderate danger	Failure could cause a very minor or no injury but annoys customers and/or results in minor system problems that can be overcome with minor modifications to the system or process
3		
2	Slight danger	Failure could cause no injury and the customer is unaware of the problem; however, the potential for minor injury exists. There is little or no effect on the system
1	No danger	Failure causes no injury and has no impact on the system

Table 6
Detection rating scale (Silva et al., 2014).

Rating	Description	Definition
10	No chance of detection	There is no known mechanism for detecting the failure.
9	Very remote/unreliable chance of detection	The failure can be detected only with a thorough inspection, and this is not feasible or cannot be readily performed
8		
7	Remote chance of detection	The error can be detected with a manual inspection, but no process is in place, so that detection left to chance
6		
5	Moderate chance of detection	There is a process for double-checks or inspections, but it is not automated and/or is applied only to a sample and/or relies on vigilance
4	High chance of detection	There is 100% inspection or review of the process, but it is not automated
3		
2	Very high chance of detection	There is 100% inspection of the process, and it is automated
1	Almost certain chance of detection	There are automatic "shut-offs" or constraints that prevent failure

Table 7
Equivalent fuzzy numbers (Wang et al., 2009a).

Crisp number	Equivalent fuzzy number
1	(1, 1, 2)
2	(1, 2, 3)
3	(2, 3, 4)
4	(3, 4, 5)
5	(4, 5, 6)
6	(5, 6, 7)
7	(6, 7, 8)
8	(7, 8, 9)
9	(8, 9, 10)
10	(9, 10, 10)

Step 4. Construct the weighted fuzzy group decision matrix

Considering the different significance of each criterion, the weighted normalized fuzzy decision matrix $\widetilde{R}' = [\widetilde{r}'_{ij}]_{m\times n}$ can be constructed by Eq. (22) (Liu et al., 2015a):

$$\widetilde{r}'_{ij} = (r'_{ij1},r'_{ij2},r'_{ij3}) = \overline{W}_j \otimes \widetilde{r}_{ij} = (\overline{W}_j r_{ij1},\overline{W}_j r_{ij2},\overline{W}_j r_{ij3}) \tag{22}$$

where $\overline{W}_j s$ are the weights of criteria obtained from previous step.

Step 5. Implement the ratio system

For the sake of optimization, the assessments of decision makers are summed in case of maximization and subtracted in case of minimization for each alternative (Liu et al., 2015a):

$$\widetilde{y}_i = \oplus_{j=1}^{g}\widetilde{x}'_{ij} \ominus \oplus_{j=g+1}^{n}\widetilde{x}'_{ij} \tag{23}$$

where $i = 1,2,...,g$ are the criteria to be maximized; $i = g + 1,g + 2,...,n$ are the criteria to be minimized; and $\widetilde{y}_i$ is the overall assessment of alternative A_i with respect to all criteria. Then, to compute the weight of each criterion in this step, the ratio of each fuzzy number of each criterion with summed value of them, is calculated by the proposed ranking fuzzy numbers method.

Step 6. Implement the reference point approach

The reference point theory is based on the weighted normalized fuzzy decision matrix $\widetilde{R}' = [\widetilde{r}'_{ij}]_{m\times n}$ obtained by Eq. (22), whereby a maximal objective reference point (MORP) is also deduced. Since the elements $\widetilde{r}'_{ij}$,∀ i,j are normalized positive triangular fuzzy numbers belonging to the closed interval [0,1], we are able to define the fuzzy MORP as $\widetilde{r}^*_j = (1,1,1)$ and $\widetilde{r}^*_j = (0,0,0)$ for benefit and cost criteria, respectively. Then, it comes to the distance matrix $D = [d_{ij}]_{m\times n}$ by Eq. (24) (Liu et al., 2015a):

$$d_{ij} = d(\widetilde{r}'_{ij},\widetilde{r}^*_j) = \sqrt{1/3[(r'_{ij1}-r^*_{j1})^2 + (r'_{ij2}-r^*_{j2})^2 + (r'_{ij3}-r^*_{j3})^2]} \tag{24}$$

where the distance d_{ij} indicates the gap of alternative A_i in the j th criterion, C_j. The distance of each alternative from fuzzy MORP can be measured by Eq. (25) (Liu et al., 2015a):

$$d_i = \max_j d_{ij} \tag{25}$$

Weight of each criterion in this step is calculated by Eq. (26):

$$w_i = \frac{1-d_i}{\sum_j (1-d_i)} \tag{26}$$

Step 7. Implement the full multiplicative form

The overall utility of the ith alternative can be expressed as a triangular fuzzy number by Eq. (27) (Liu et al., 2015a):

$$\widetilde{u}_i = \widetilde{a}_i \o \widetilde{b}_i \tag{27}$$

where $\widetilde{a}_i = \otimes_{j=1}^{g}\widetilde{x}'_{ij}$ denotes the product of criteria of the ith alternative to be maximized with $g = 1,2,...,n$ being the number of criteria to be maximized and where $\widetilde{b}_i = \otimes_{j=g+1}^{n}\widetilde{x}'_{ij}$ denotes the product of criteria of the ith alternative to be minimized with n–g being the number of criteria to be minimized. Then, to compute the weight of each criterion in this step, the ratio of each fuzzy number of each criterion with summed value of them is calculated by the proposed ranking fuzzy numbers method.

Step 8. Calculate the final weights of each criterion

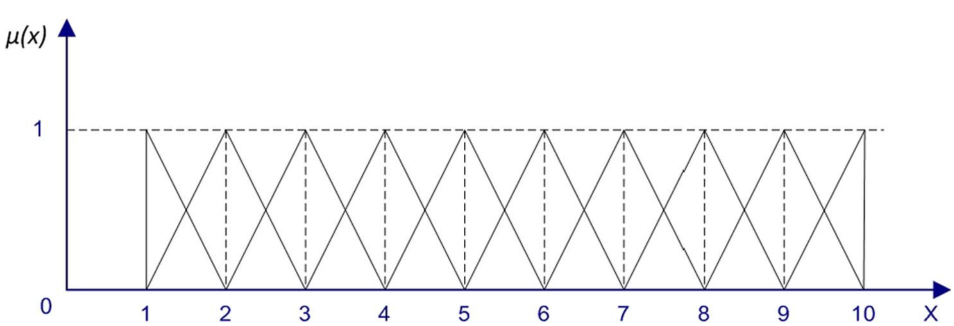

Fig. 5. Fuzzy environment (Wang et al., 2009a).

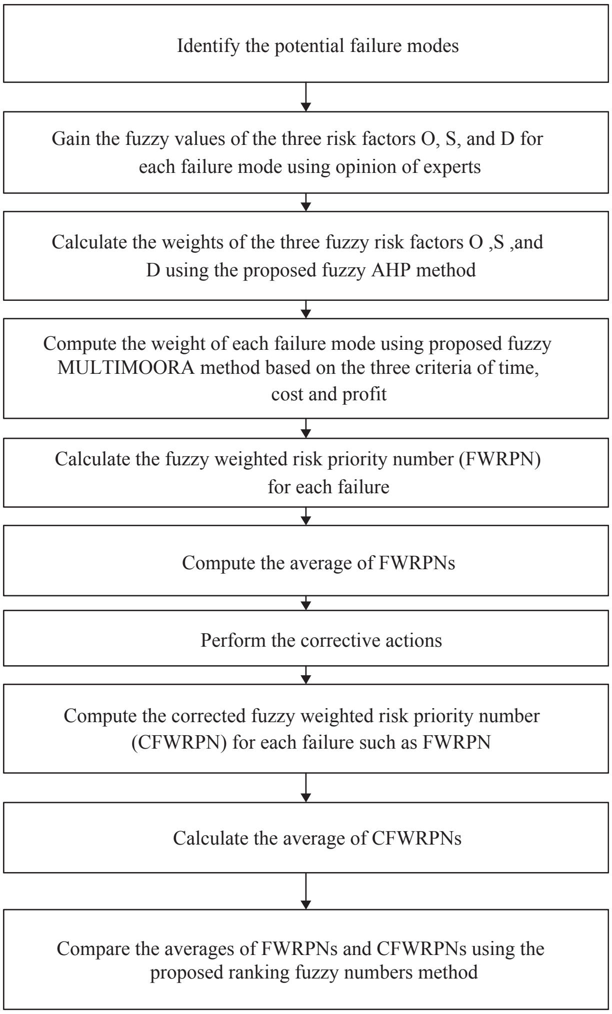

Fig. 6. The proposed hybrid method based on fuzzy FMEA and extended fuzzy MULTIMOORA and fuzzy AHP methods.

Table 8
The fuzzy values of the three risk factors for each occupational accident in Kerman Steel Industries Factory.

Type of accident	Severity (S)	Occurrence (O)	Detection (D)
Hot bars contacting hands	(5, 6, 7)	(3, 4, 5)	(3, 4, 5)
Slipping	(5, 6, 7)	(3, 4, 5)	(3, 4, 5)
Accidents by heavy wrench	(6, 7, 8)	(3, 4, 5)	(4, 5, 6)
Fingers stuck under the wheels of vertical motion	(9, 10, 10)	(1, 2, 3)	(1, 2, 3)
Fingers stuck between rollers	(9, 10, 10)	(1, 2, 3)	(1, 2, 3)
Electromotors falling on hands	(8, 9, 10)	(2, 3, 4)	(2, 3, 4)
Plates falling on the feet	(8, 9, 10)	(2, 3, 4)	(2, 3, 4)
Rollers falling on the feet	(8, 9, 10)	(2, 3, 4)	(2, 3, 4)

Table 9
Fuzzy pair-wise comparison matrix for the three risk criteria and the weight of each criterion.

Criterion	Severity (S)	Occurrence (O)	Detection (D)	Weight
Severity (S)	(1, 1, 1)	(1, 1, 1.5)	(1, 1.5, 2)	0.387
Occurrence (O)	(2/3, 1, 1)	(1, 1, 1)	(1, 1, 1.5)	0.330
Detection (D)	(1/2, 2/3, 1)	(2/3, 1, 1)	(1, 1, 1)	0.283

In the proposed method, the final weight of each criterion is obtained by the arithmetic mean of the weights calculated in steps 5, 6, and 7.

4. The proposed hybrid method based on fuzzy FMEA and extended fuzzy MULTIMOORA and fuzzy AHP methods

The steps of the proposed method are as follows:

Step 1. Potential failure modes are identified.
Step 2. The crisp values of the three risk factors O, S, and D, are obtained for each failure mode by experts considering Tables 4–6 and the fuzzy values of them are obtained from Table 7. Moreover, the fuzzy environment is given in Fig. 5.
Step 3. The weights of the three fuzzy risk factors O, S, and D are calculated by the proposed fuzzy AHP method (W_O, W_S and W_D).
Step 4. The weight of each failure mode (W_{F_i}) is computed by the proposed fuzzy MULTIMOORA method based on the three criteria of time (the required time to perform the proposed corrective actions for decreasing or eliminating the effects of failure), cost (the required cost to conduct the proposed corrective actions for decreasing or eliminating the effects of failure), and profit (the profit obtained from decreasing or eliminating the effects of failure) using fuzzy linguistic terms.
Step 5. The fuzzy weighted risk priority number (FWRPN) for each failure is calculated by multiplying three fuzzy risk factors O, S, and D by weights of the three factors and the weight of each failure mode obtained from steps 2, 3, and 4, respectively.
Step 6. The average of FWRPNs (AFWRPNs) is calculated by Eqs. (3) and (6).
Step 7. The corrective actions are performed for decreasing or eliminating the identified failures and their effects.
Step 8. The corrected fuzzy weighted risk priority number (CFWRPN) is computed for each failure such as FWRPN.
Step 9. The average of CFWRPNs (ACFWRPNs) is calculated like step 6.
Step 10. AFWRPNs and ACFWRPNs are compared by the proposed ranking fuzzy numbers method.

Fig. 6 shows the steps of the proposed hybrid method.

5. Application and results

In order to demonstrate the applicability and benefits of the proposed fuzzy hybrid method, Kerman Steel Industries Factory is considered as a case study. Kerman Steel Industries Factory has been constructed in the vicinity of the city of Bardsir (45 km southwest of the city of Kerman) in country of Iran. After 25 years of activity, it is known as one of the complementary providers of the production chain actively participating in the national and regional areas of steel industry. This factory is currently working at production capacity of 220,000 tons. Production units and quantometric, metallography, mechanical properties, and calibration laboratories are the most important departments of the factory.

The justification behind choosing a single case lies in what Yin (1994) put forth. He maintained that using multiple cases should be investigated in distinct and multiple experiments and not in a single survey. He contended that the rationale behind this choice is that of replication not sampling.

In this case study, occupational accidents of the mentioned factory were investigated as failure modes. In the current study, five decision makers (DMs) participated in identifying and analyzing occupational accidents of the factory. The DM team consisted of five experts working at the factory with more than 10 years of experience including one

Table 10
Linguistic assessments of each occupational accident provided by the five decision makers.

Type of accident	Time					Cost					Profit				
	DM_1	DM_2	DM_3	DM_4	DM_5	DM_1	DM_2	DM_3	DM_4	DM_5	DM_1	DM_2	DM_3	DM_4	DM_5
Hot bars contacting hands	VL	VL	L	L	VL	L	VL	L	L	VL	M	M	M	MH	M
Slipping	VL	VL	L	VL	L	VL	L	L	VL	L	M	M	ML	M	M
Accidents by heavy wrench	VL	VL	L	VL	L	L	L	VL	L	VL	M	MH	M	MH	MH
Fingers stuck under the wheels of vertical motion	VL	VL	VL	VL	L	VL	VL	VL	L	L	VH	H	VH	VH	H
Fingers stuck between rollers	VL	VL	VL	L	VL	L	VL	VL	VL	L	VH	H	VH	VH	VH
Electromotors falling on hands	L	VL	VL	VL	L	L	L	L	VL	VL	H	H	M	H	M
Plates falling on the feet	VL	VL	VL	VL	L	VL	VL	VL	L	L	H	H	VH	H	VH
Rollers falling on the feet	VL	L	VL	VL	VL	VL	VL	L	VL	L	H	H	VH	H	H

Table 11
The weights of occupational accident in Kerman Steel Industries Factory provided by the proposed fuzzy MULTIMOORA method.

Type of accident	Weight
Hot bars contacting hands	0.067
Slipping	0.054
Accidents by heavy wrench	0.079
Finger stuck under the wheels of vertical motion	0.178
Fingers stuck between rollers	0.183
Electromotors falling on hands	0.093
Plates falling on the feet	0.175
Rollers falling on the feet	0.171

Table 13
The fuzzy values of the three risk factors for each occupational accident in Kerman Steel Industries Factory after the corrective actions were done.

Type of accident	Severity (S)	Occurrence (O)	Detection (D)
Hot bars contacting hands	(3, 4, 5)	(2, 3, 4)	(2, 3, 4)
Slipping	(3, 4, 5)	(2, 3, 4)	(2, 3, 4)
Accidents by heavy wrench	(4, 5, 6)	(2, 3, 4)	(3, 4, 5)
Fingers stuck under the wheels of vertical motion	(9, 10, 10)	(1, 1, 2)	(1, 2, 3)
Fingers stuck between rollers	(9, 10, 10)	(1, 1, 2)	(1, 2, 3)
Electromotors falling on hands	(8, 9, 10)	(1, 2, 3)	(2, 3, 4)
Plates falling on the feet	(7, 8, 9)	(1, 2, 3)	(1, 2, 3)
Rollers falling on the feet	(7, 8, 9)	(1, 2, 3)	(1, 2, 3)

production line manager, two health, safety and environment (HSE) inspectors, one foreman and one worker from the production line. Also, the priority (priority weight) for all decision makers was considered equal in identifying and analyzing occupational accidents of the factory. The DMs were represented as DM_1, DM_2, DM_3, DM_4 and DM_5.

The proposed fuzzy hybrid method was applied step-by-step for the case study as it was stated in Section 4. First, occupational accidents of the factory are identified as failure modes by DM team. Based on the gathered data from the factory, eight types of occupational accidents resulting in considerable damages to the workers were detected. It should be noted that more accidents were detected in this study, but as they were less important and for the sake of simplicity, they were neglected and limited to eight important ones. The identified eight accidents in the factory included hot bars contacting hands, slipping, accidents by heavy wrench, fingers stuck under the vertical motions of the wheels, fingers stuck between the rollers, electro motors falling on hands, plates falling on feet, and rollers falling on feet.

Then, the crisp values of the three risk factors of O, S, and D, were obtained for each accident by DM team considering Tables 4–6 and the fuzzy values of them have been obtained by using Table 7. Table 8 demonstrates the fuzzy values of the three risk factors of O, S, and D.

Afterwards, the weights of the three fuzzy risk factors of O, S, and D were calculated by the proposed fuzzy AHP method (W_O, W_S and W_D). For this purpose, hierarchical structure of AHP method was determined for the problem. Then, the fuzzy pair-wise comparison matrix for criteria (O, S and D) with regard to the objective was formed by DM team, considering Table 2. Subsequently, the fuzzy numbers of each column were summed by using Eq. (3). In the next step, the ratio of each fuzzy number with the obtained summed value for each column was calculated by the proposed ranking fuzzy numbers method. Finally, the weight of each criterion was obtained by the arithmetic mean of the numbers in each row. Table 9 illustrates the fuzzy pair-wise comparison matrix for the three risk criteria and the weight of each criterion obtained by the proposed AHP method. As Table 9 shows, severity factor was more important than the other risk factors in this case study.

The reason for applying the weights of the three fuzzy risk factors of O, S, and D to the proposed fuzzy hybrid method is that the RPN for each failure mode be computed more precisely. In the conventional FMEA, sometimes the difference between some failure modes cannot be distinguished because the relative importance (weight) of the three risk factors is not considered, so different combinations of the three risk factors of O, S, and D may produce exactly the same value of RPN; however, their hidden risk implications may be totally different. Accordingly, in the proposed fuzzy hybrid method, the weights of the three fuzzy risk factors were applied to calculate the RPN for each failure mode.

In the next step, the weight of each identified occupational accident was computed by the proposed fuzzy MULTIMOORA method based on the three criteria of time (the required time to perform the proposed

Table 12
The calculated FWRPNs and AFWRPN.

Type of accident	FWRPN	AFWRPNs
Hot bars contacting hands	(0.109, 0.232, 0.424)	
Slipping	(0.088, 0.187, 0.341)	
Accidents by heavy wrench	(0.205, 0.400, 0.685)	
Finger stuck under the wheels of vertical motion	(0.058, 0.257, 0.579)	
Fingers stuck between rollers	(0.059, 0.264, 0.595)	
Electromotors falling on hands	(0.107, 0.272, 0.538)	
Plates falling on the feet	(0.202, 0.512, 1.012)	
Rollers falling on the feet	(0.198, 0.501, 0.989)	
		(0.128, 0.328, 0.645)

Table 14
The calculated CFWRPNs and ACFWRPNs.

Type of accident	CFWRPN	ACFWRPNs
Hot bars contacting hands	(0.029, 0.087, 0.194)	
Slipping	(0.023, 0.070, 0.156)	
Accidents by heavy wrench	(0.068, 0.171, 0.343)	
Finger stuck under the wheels of vertical motion	(0.058, 0.064, 0.257)	
Fingers stuck between rollers	(0.059, 0.066, 0.264)	
Electromotors falling on hands	(0.054, 0.181, 0.403)	
Plates falling on the feet	(0.044, 0.202, 0.512)	
Rollers falling on the feet	(0.043, 0.198, 0.501)	
		(0.047, 0.130, 0.329)

Table 15
Comparison of AFWRPNs and ACFWRPNs.

AFWRPNs	ACFWRPNs	Ratio
(0.128, 0.328, 0.645)	(0.047, 0.130, 0.329)	0.44

Table 16
AFWRPNs, ratios, and percentages of them with respect to the considered cases.

	Case 1	Case 2	Case 3	Case 4
	$W_S = 0.387$ $W_O = 0.330$ $W_D = 0.283$	$W_S = 0.7$ $W_O = 0.2$ $W_D = 0.1$	$W_S = 0.1$ $W_O = 0.8$ $W_D = 0.1$	$W_S = 0.1$ $W_O = 0.3$ $W_D = 0.6$
AFWRPNs	(0.128, 0.328, 0.645)	(0.050, 0.127, 0.250)	(0.028, 0.073, 0.143)	(0.064, 0.163, 0.321)
Ratio	1	0.388	0.222	0.479
Percentage of variations	0	−61.2%	−77.8%	-52.1%

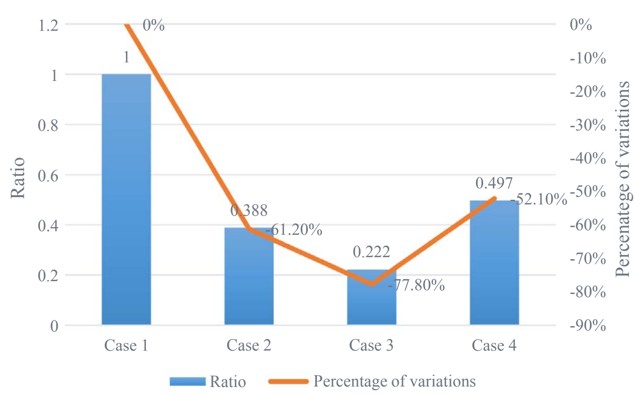

Fig. 7. Sensitivity analysis of the proposed fuzzy hybrid method.

corrective actions for decreasing or eliminating the effects of failure), cost (the required cost to conduct the proposed corrective actions for decreasing or eliminating the effects of failure), and profit (the profit obtained from decreasing or eliminating the effects of failure) using fuzzy linguistic terms. Table 10 shows linguistic assessments of each occupational accidents provided by five decision makers. The weights of failure modes achieved by the proposed fuzzy MULTIMOORA method are also presented in Table 11. According to Table 11, fingers stuck between rollers has higher priority and weight in terms of time, cost and profit than other accidents in the calculations of RPN.

Since RPN indicates the risk priority number, there is higher priority to deal with the failure mode with higher RPN to receive more immediate appropriate corrective actions. The reason for applying the proposed fuzzy MULTIMOORA method to calculate the weight of each failure mode is to understand what impacts decreasing or eliminating the effects of a failure in terms of time, cost and profit has on the system. In other words, with incorporating the obtained weights of the failure modes by the proposed fuzzy MULTIMOORA method in calculations of RPN, the impacts of decreasing or eliminating the effects of the failure in terms of time, cost and profit on the system are considered. Therefore, for the failure which needs less time and lower cost for decreasing or eliminating its effects and also the organization gains more profit from decreasing or eliminating its effects, higher weight should be considered for it in the RPN calculations. Accordingly, the organization should conduct proper corrective actions on this failure mode having higher RPN sooner than dealing with other failure modes because of its higher risk and organization resource constraints. As a result, the organization can manage the time, cost and profit of decreasing or eliminating failure effects using appropriate corrective actions.

Next, the fuzzy weighted risk priority number (FWRPN) for each identified occupational accident was calculated by multiplying three fuzzy risk factors of O, S, and D by the weights of the three factors and the weight of each occupational accident obtained from the previous steps. Then, the average of FWRPNs (AFWRPNs) was calculated by Eqs. (3) and (6). Table 12 demonstrates the calculated FWRPNs and AFWRPNs.

Afterwards, the appropriate corrective actions were performed for decreasing and eliminating the identified occupational accidents and their effects. In this factory the workers of each department were specialized persons in their field, therefore, they unfortunately would get used to the routine of it and they would then ignore some safety measures. According to the nature of the identified accidents, corrective actions generally consist of periodic trainings, retraining courses, improvement of personal security tools (e.g. having safety gloves, helmets, and earplugs), and also installing safety sings and warnings in order to remind the workers of the accidents and potential risks in the corresponding work place. Table 13 shows the fuzzy values of the three risk factors for each occupational accident in the factory after the corrective actions were executed.

In the next step, the corrected fuzzy weighted risk priority number (CFWRPN) was computed for each occupational accident such as FWRPN and the average of CFWRPNs (ACFWRPNs) was calculated like AFWRPNs. Table 14 demonstrates the calculated CFWRPNs and ACFWRPNs.

Finally, AFWRPNs and ACFWRPNs were compared by the proposed ranking fuzzy numbers method. As it is shown in Table 15, the ratio between AFWRPNs and ACFWRPNs was calculated 0.44. In other words, the ACFWRPNs decreased by 56% compared to the AFWRPNs. As a result, the identified occupational accidents in Kerman Steel Industries Factory and their effects were reduced more than 50% based on the results obtained from the proposed fuzzy hybrid method. Therefore, it can be concluded that the applicability of the proposed fuzzy hybrid method in this case study was effective and beneficial.

A sensitivity analysis is performed to validate the performance of the results of the proposed novel fuzzy hybrid method which is based on fuzzy FMEA, extended fuzzy MULTIMOORA, and fuzzy AHP methods.

To this aim, the weights of the three fuzzy risk factors of O, S, and D calculated by the proposed fuzzy AHP method (W_O, W_S and W_D) are changed. Four cases are taken into consideration during sensitivity analysis. Case 1 is Kerman Steel Industries Factory and other cases are new with different weights of the three fuzzy risk factors of O, S, and D. Table 16 demonstrates these different cases. It also illustrates the ratios between the AFWRPNs of new cases and the calculated AFWRPNs of Kerman Steel Industries Factory and new cases' AFWRPNs percentages of variations compared to AFWRNPs of Kerman Steel Industries Factory using the proposed novel ranking fuzzy numbers. The results of sensitivity analysis are depicted in Fig. 7. The sensitivity analysis indicates that the weights of the three fuzzy risk factors of O, S, and D calculated by the proposed fuzzy AHP method can have a significant influence on the average of fuzzy weighted risk priority number (AFWRPNs). Therefore, in the real-world cases, determining proper weights of the three fuzzy risk factors of O, S, and D according to real situations and experts' opinions is of importance and benefit to the risk prioritization of failure modes and then the following corrective actions. Based on the conducted sensitivity analysis, this paper finds that the proposed fuzzy hybrid method can end in reasonable results and provide suitable information to evaluate various failure modes more precisely.

All in all, the benefits of using the proposed fuzzy hybrid method in this case study are as follows. First, more precise RPN calculation because of using the weights of the three risk factors and the weights of each failure mode (occupational accidents) simultaneously, in other words, using weighted fuzzy risk priority number (WFRPN) instead of conventional RPN. Second, managing the time, cost, and profit of decreasing or eliminating failure effects using appropriate corrective actions by calculating the weight of each identified failure mode utilizing the proposed fuzzy MULTIMOORA method based on the three criteria of time, cost, and profit. Third, using more accurate fuzzy numbers calculations due to the use of a precise novel ranking fuzzy numbers method. Finally, performing appropriate corrective actions on different failure modes and reducing ACWFRPN compared to AWFRPN.

6. Conclusion and future remarks

Risk evaluation is defined as a method which is logically used for determining quantitative and qualitative risks value and investigating potential consequences. One of the most important risk assessment tools, FMEA, has been extensively used in different industries and organizations. In order to evaluate various failure modes more precisely the suggested novel fuzzy hybrid method based on fuzzy FMEA, extended fuzzy MULTIMOORA, and fuzzy AHP methods were proposed in this paper in which the weights of the three risk factors and the weight of each failure mode were calculated by the extended fuzzy AHP and fuzzy MULTIMOORA methods, respectively. In other words, in the proposed method, the weights of the three risk factors and the weights of each failure mode were considered simultaneously. This resulted in more precise calculations of RPNs as well as the improved the effectiveness of the FMEA method. Instead of utilizing RPN for each failure, this method benefited from the fuzzy weighted risk priority number (FWRPN).

In this method, the weight of each failure mode was computed by the proposed fuzzy MULTIMOORA method on the basis of three criteria of time, cost, and profit. After calculating FWRPN for each failure, proper following corrective actions were conducted to either eliminate the identified failures or decrease their impacts and for each failure the corrected fuzzy weighted risk priority number (CFWRPN) was computed. Finally, the average of FWRPNs (AFWRPNs) was compared with the average of CFWRPNs (ACFWRPNs) to evaluate the effectiveness of corrective actions by the use of the novel ranking fuzzy numbers method. As a case study, the risk of occupational accidents in Kerman Steel Industries Factory was evaluated by the novel fuzzy hybrid method. According to the obtained results, the FWRPNs of occupational accidents in the factory were high. Therefore, suitable corrective actions were performed in order to reduce the accidents. After implementing the corrective actions, the effectiveness of these actions was evaluated. For this purpose, the novel fuzzy number ranking was applied to compare the average of FWRPNs (AFWRPNs) with the average of CFWRPNs (ACFWRPNs). Eventually, a sensitivity analysis was performed to validate the obtained results. Findings showed that AFWRPNs decreased by 56% compared to ACFWRPNs.

As a future remark, it is suggested to validate the reliability of the proposed method in other case studies, different industries, and various countries. Moreover, further studies might be useful to extend the proposed model by the applications of the new MCDM methods. Using a new method for ranking fuzzy numbers to compare the fuzzy numbers in the proposed MCDM methods is another suggestion for future research.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ssci.2017.10.018.

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